

A System-of-Systems Modeling Methodology for Strategic General Aviation Design Decision-Making

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A System-of-Systems Modeling Methodology for Strategic General Aviation Design Decision-Making

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Nomenclature

Mi	Simulation Code Mi
ALCCA	Aircraft Life Cycle Cost Analysis
APT	Advanced Performance Technology Suite
ATS	1995 American Travel Survey
BTS	Bureau of Transportation
E2F	Easy-to-Fly Technology
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FLOPS	FLight Optimization System
GA	General Aviation
GAATA	General Aviation and Air Taxi Activity Survey
GAJ	General Aviation Jet
GAMA	General Aviation Manufacturers Association
GAP	General Aviation Piston
MSA	Metropolitan Statistical Area
NTS	National Transportation System
O/D	Origin - Destination Matrix
QFD	Quality Function Deployment
SEP	Single Engine Piston
SP	Service Provider
TOC	Total Operating Cost
UTE	Unified Tradeoff Environment
VLJ	Very Light Jet
ACQ	Acquisition cost
C	Component cost to customer
D	Demand quantity
d	Distance between locales
DOC	Direct operating cost
FF	Fuel flow
fl	Fleet loading
OEC	Overall evaluation criteria
P	Profit metric
p	Rental rate

pax	Passenger capacity
$pMarkUp$	Rental rate mark up
Pop	Population at locale
Q	Quantity Metric
R	Mission range
V	Flight speed

SUMMARY

General aviation has long been studied as a means of providing an on-demand "personal air vehicle" that bypasses the traffic at major commercial hubs. This thesis continues this research through development of a system of systems modeling methodology applicable to the selection of synergistic product concepts, market segments, and business models.

From the perspective of the conceptual design engineer, the design and selection of future general aviation aircraft is complicated by the definition of constraints and requirements, and the tradeoffs among performance and cost aspects. Qualitative problem definition methods have been utilized, although their accuracy in determining specific requirement and metric values is uncertain. In industry, customers are surveyed, and business plans are created through a lengthy, iterative process.

In recent years, techniques have developed for predicting the characteristics of US travel demand based on travel mode attributes, such as door-to-door time and ticket price. As of yet, these models treat the contributing systems - aircraft manufacturers and service providers - as independently variable assumptions.

In this research, a methodology is developed which seeks to build a strategic design decision making environment through the construction of a system of systems model. The demonstrated implementation brings together models of the aircraft and manufacturer, the service provider, and most importantly the travel demand. Thus represented is the behavior of the consumers and the reactive behavior of the suppliers - the manufacturers and transportation service providers - in a common modeling framework.

The results indicate an ability to guide the design process - specifically the selection of design requirements - through the optimization of "capability" metrics. Additionally, results indicate the ability to find synergetic solutions, that is solutions in which two systems might collaborate to achieve a better result than acting independently.

Implementation of this methodology can afford engineers a more autonomous perspective in the concept exploration process, providing dynamic feedback about a design's potential success in specific market segments. The method also has potential to strengthen the connection between design and business departments, as well as between manufacturers, service providers, and infrastructure planners - bringing information about how the respective systems interact, and what might be done to improve synergism of systems.

Chapter I

INTRODUCTION

“Our current air transportation system is severely limited in its ability to accommodate America’s growing need for mobility...superior mobility afforded by air transportation is a huge national asset and competitive advantage for the United States.” -Commission on the Future of the United States Aerospace Industry, 2002

1.1 General Aviation as a Travel Mode

As the nation’s demand for air mobility continues to grow, the capability to satisfy that demand is in question. Efforts to enhance the current National Air Transportation System exist, but many believe these plans will not be enough to satisfy a large portion of the demand (AIA, 2002). A comparison of demand forecasts and capacity enhancement plans imply a demand-capacity mismatch of as many as 50 million trips per year by 2020¹.

As an alternative to commercial air carriers, General aviation² (GA) has some major growth potential advantages. First, the infrastructure is largely in place. There are over 5,000 public use runways in the U.S., of which over 95% are usable by the average single engine piston aircraft, and over 50% usable by the average business jet, see Figure 1. Most of these runways see little use, as the commercial airline hub-and-spoke networks channel most flights through a small number of airports.

¹For an overview of the supporting statistics, refer to Appendix A

²The term GA includes all aviation operations other than scheduled commercial air carriers and military, with aircraft types ranging from balloons to large multi-turbine transports, and operations ranging from sightseeing to medical transport. For the purposes of this thesis, usage of GA is limited to personal and business transportation. This includes on-demand air carriers, commonly known as air taxi, which operate under part 135 of the Federal Aviation Regulations (FAR).

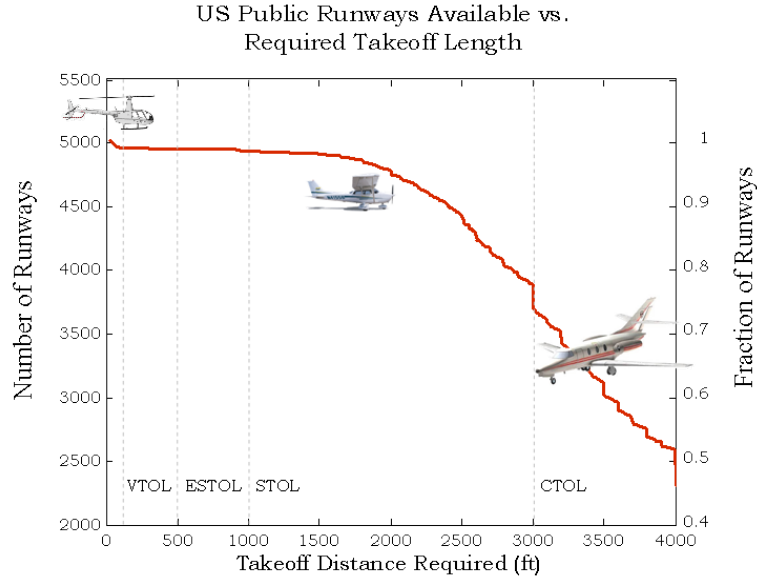


Figure 1: US public runway availability v. required takeoff field length.

The utilization of GA has seen hopeful periods of growth, but not enough to sustain its expectations as a common mode of transportation. Half a century ago, many thought it inevitable that the “flying car” would be the dominant mode of future travel by the turn of the century. Instead, GA captures only a small portion of the travel market, as seen in Figure 2.

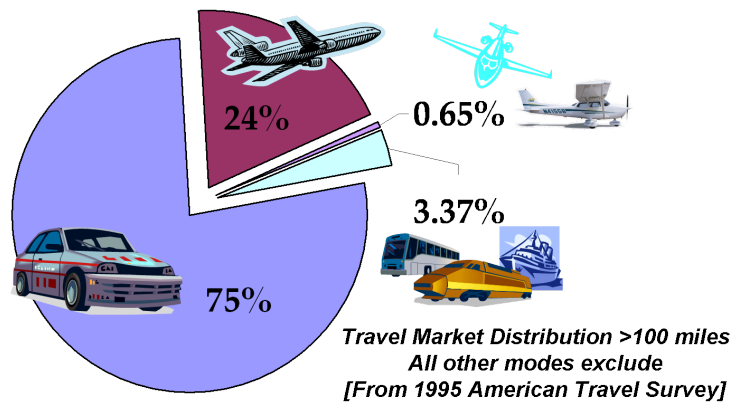


Figure 2: Travel market distribution (BTS, 1997).

Some blame the detrimental technology-cost cycle, in which low demand has not brought

in the revenues to fund attractive technology innovation, and vice versa (Wells, 1987). Additionally, the collapse of the industry in the 1970's, just as it reached a record volume of sales, has been blamed on liability lawsuits brought against the manufacturers, where after annual shipments plunged from 18,000 to 2,000 aircraft in just a few years (Truitt and Tarry, 1995). Additionally, there has been a disparity in the usage trends of piston aircraft, which continues to decline, and jet aircraft, which is in a period of rapid growth. These trends point to the costly nature of GA, which over time appears to be evolving to a travel mode for only the most wealthy. While this segment of the GA market is important, widespread growth is limited to a small portion of the population which find travel by business jet an affordable endeavor.

There are new hopes for a boom in GA. The General Aviation Revitalization Act of 1994 was put in place in part to protect manufacturers from liability lawsuits. On the technology side, a combination of maturity in autonomous and semi-autonomous control algorithms³, GPS-based mapping and navigation software and hardware, now commonplace, and Federal Aviation Administration (FAA) plans for automated air traffic control systems⁴, could make pilots more comfortable with utilizing their aircraft, as well as induce growth in the pilot population. Improving manufacturing methods can reduce the cost of aircraft, while simultaneously allowing lighter airframes and better aerodynamic shaping (Smith, 2006b). If these technologies can be successfully applied to GA aircraft and infrastructure, there exists a potential for a significant impact, and with that perhaps new and evolving GA markets.

1.2 Research Scope

In the prospect of a large growth in GA, research will be needed to shape the problem - identify what future GA travelers want - and to identify, explore, and order the space of potential design solutions. These topics incorporate the conceptual design phase, for which numerous methodologies and tools have been developed, although few have been applied to GA.

³Autonomous UAVs are expanding their capabilities rapidly, see for example Ippolito et al. (2007); their control algorithms could be applied to manned aircraft.

⁴See www.faa.gov for a summary of FAA's NextGen plan.

General aviation conceptual design differs from other aircraft types largely because the customers are a large group of individuals, as depicted by Figure 3. On the other hand, commercial air transports are designed toward the specifications of the air carriers who determine the best size and range to capture markets and profits. Military aircraft are designed toward a specific set of performance capabilities, set by military planners, which will accomplish a certain mission capability.

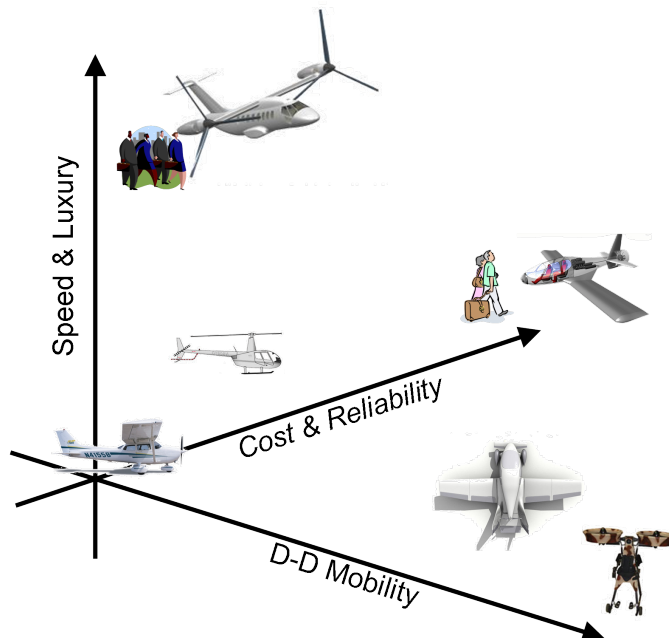


Figure 3: Future GA: directions of customer preference and aircraft requirements.

In the current GA industry, manufacturers have built a familiarity with its customer base - a relatively small group of enthusiasts and wealthy travelers. But, if the future brings beneficial technology, planning, and policy, then new customer dimensions may develop, and many questions may arise. Will new customers bring a shift in design preferences? What changes in design will give manufacturers and service providers a competitive advantage? What designs will agree best with national goals, such as mobility, safety, and environmental concerns? Should funding be aimed at high performance, “takeoff from your driveway” capability, such as in the Personal Air Vehicle Exploration program (See (Moore, 2001, 2003) for examples of typical PAV concepts and missions), or will it be better to pursue a conservative approach?

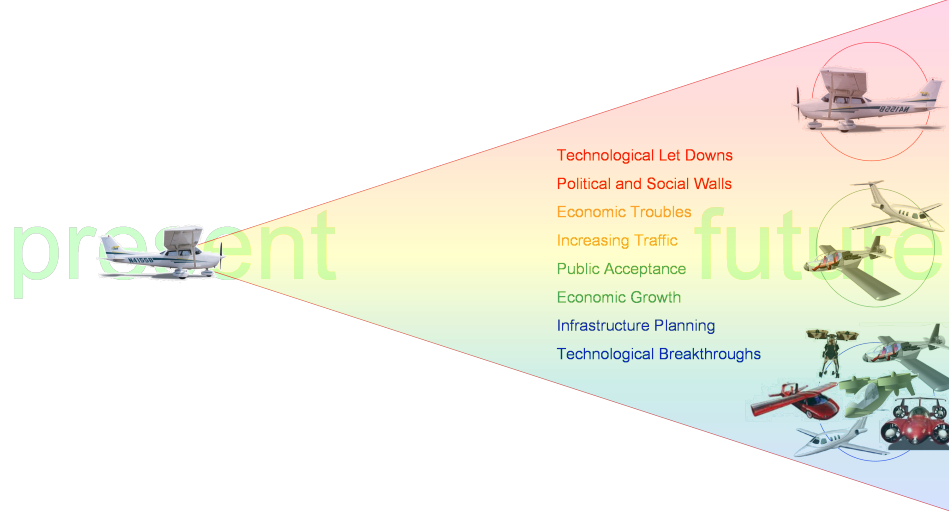


Figure 4: Future GA: a spectrum of futures.

Under this circumstance, manufacturers and researchers need tools that can help them address these questions during the conceptual design phase. As mentioned, many methods and tools have been developed to aid the conceptual designer, but there is still much progress to be made in developing tools aimed at the GA conceptual designer - a means of understanding how design changes will be received among a diverse group of customers.

Currently, industry and research groups iterate upon requirements, performance, and cost during the conceptual design phase. A generic representation of the conceptual design process is found in Figure 5. During this process, the decision makers attempt to understand and make design tradeoff decisions based upon their translations of customer desires.

Industry likely has a history of sales trends, customer surveys, and economic analysis techniques that can be used to build a problem definition, or requirements specification. Together, the data and analyses provide a solid basis for setting requirements and cost goals. Next, the engineer tries to resolve the space of solutions which satisfy the specified requirements, and works with the decision makers to decide what tradeoffs will be made - there is rarely an ideal solution. Iteration then takes place - the customers may be surveyed about the newly resolved design space, and a more detailed cost and business plan strategy may be studied. Although this method has provided industry with success for many years, it can be time consuming, and also may not apply to a revolutionary change in GA.

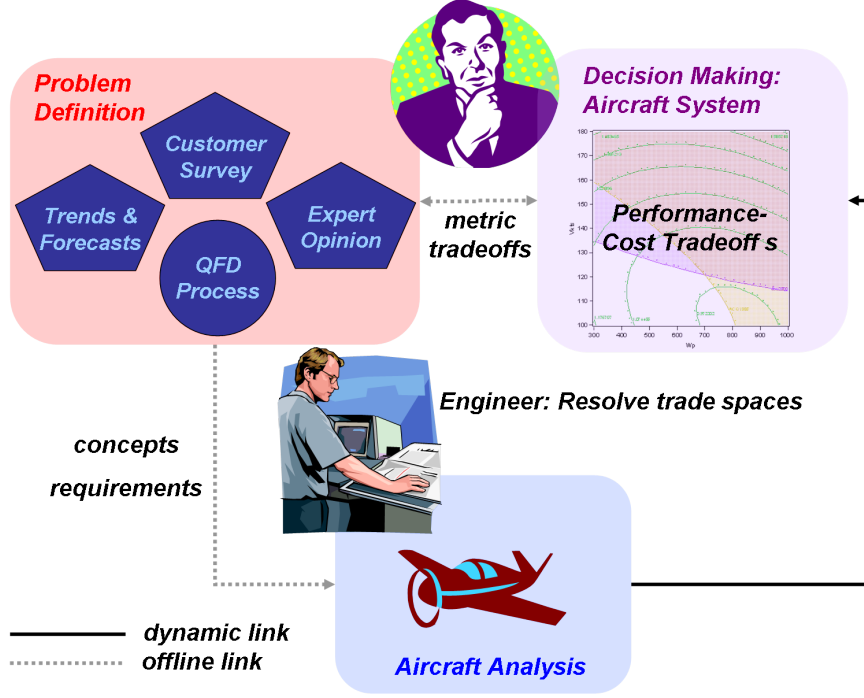


Figure 5: The traditional conceptual design process.

Exploration of revolutionary concepts - a task of academia and fundamental research - are likely aimed at customers that are not well known today. Thus, the requirements specification will require a significant amount of subjective estimations to decide who these customers are and what they will want. Although rigorous requirement and metric mapping tools and methods, e.g. Quality Function Deployment (QFD), can make the process more tractable, Hazelrigg (2003) has argued that application of subjectively designed requirements and metric preferences makes the selection process, in most design cases, arbitrary, regardless of the rigor of the methodology.

Thus, the goal of this thesis is to implement a new approach to the GA conceptual design problem - one that dynamically brings the perspective of the diverse customer population into a design environment that objectively translates aircraft system variable changes into metrics representing the capability to capture markets. This system of systems, capability-based framework is depicted in Figure 6.

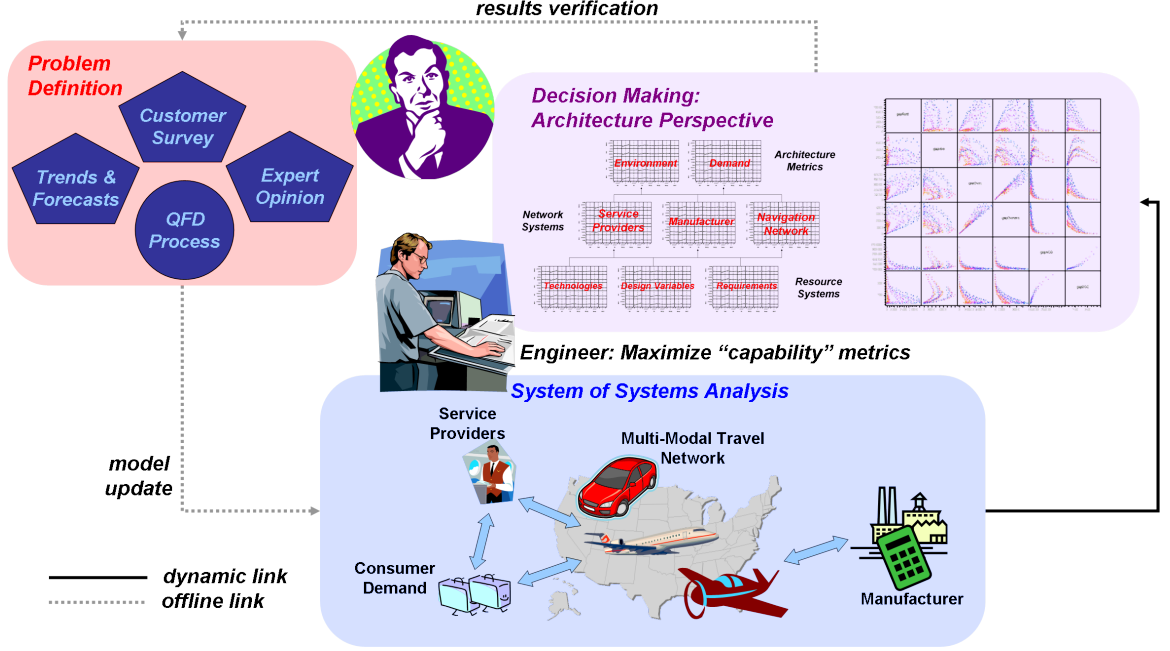


Figure 6: Conceptual depiction of capability-based framework.

Implementation of this framework could enable the conceptual design engineer to explore design alternatives - requirements, concepts, technologies, and target markets - with the perspective of other entities and decision makers at hand. The new perspective brings to the engineer a surrogate of the problem definition process, enhancing the freedom of exploration with fast “capability” assessments between the traditionally manual problem definition and concept assessment iterations. Used in an industry setting, where the designers and business strategists might manually iterate concepts, the system of systems methodology can provide a common environment to fluidize the process, while giving both sides a greater freedom to explore their options. Likewise, the methodology could be used by other entities to examine how best to implement their system. For example, a policy maker may explore what combinations of aircraft related technologies synergize with proposed changes in airspace and air traffic policies and procedures.

1.3 Thesis Organization

The remainder of this thesis is laid out to systematically track the pursuit of the research goal. The literature review, found in Chapter 2, provides insight into the current problems

faced by researchers in the conceptual design of future GA aircraft.

Chapter 2 concludes with a synopsis of the literature review, invoking the motivational and methodological research questions and hypotheses which drive this research and the development of the modeling methodology discussed in Chapter 3. Discussion relating to perspectives, for example the concept of capability-based design, relevant to the development of the methodology is available in Appendix B.

The second half of Chapter 3 begins the implementation of the methodology to the GA systems design problem - up to the point of modeling. Modeling hypotheses are also stated which address how technical challenges in modeling the system of systems will be overcome.

Formulations of the aircraft manufacturer, travel demand, and service provider system models, are found in Chapters 4-6, respectively. The integration of the system models is laid out in Chapter 7, along with verification of the baseline integrated model, and then exploration to hypothetical scenarios. Appendix C contains additional model integration information, calibration data and procedures, and additional results.

The thesis concludes with Chapter 8 with a revisitation of the hypotheses, followed by a discussion of the contributions and suggestions for future work.

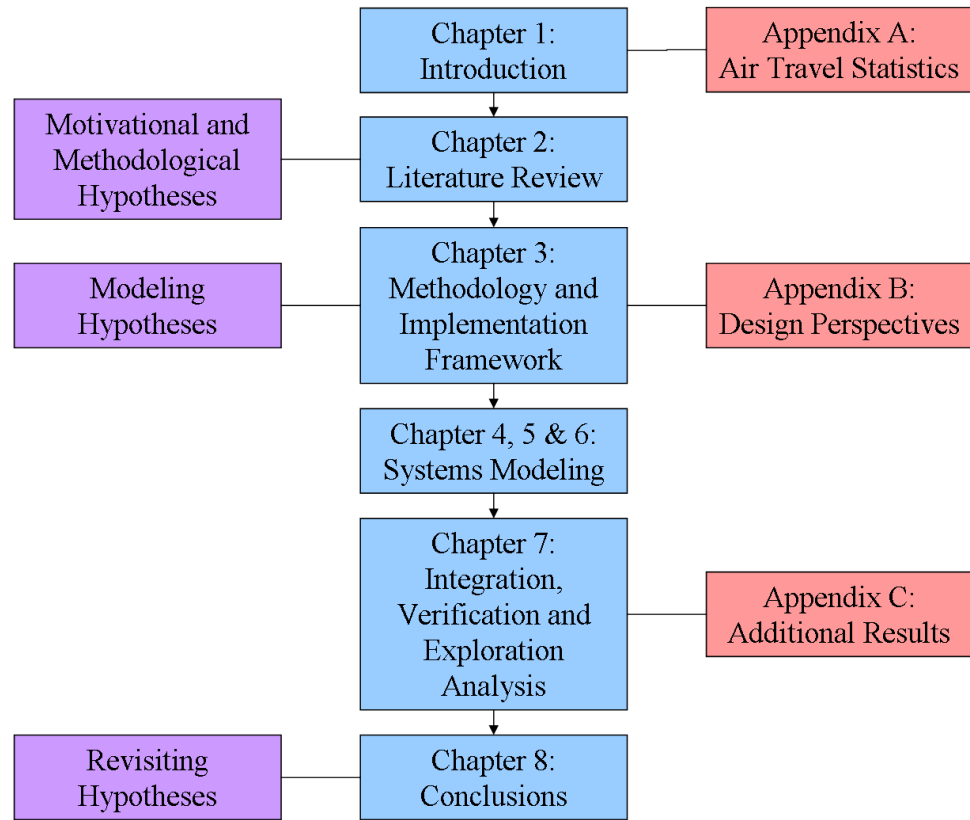


Figure 7: Organization of dissertation chapters, appendices, and hypotheses.

Chapter II

LITERATURE REVIEW

The topic of this thesis pertains ultimately to presenting a methodology for decision making in the conceptual design phase of GA aircraft. Conceptual design is defined here as the first stage of the vehicle design process that entails function specification, concept generation, and concept selection, where *concept* includes sufficient information on configuration, basic parameters of scale, performance, and cost. Requirements specification is imperative in formulating the design problem for which solutions are sought. A key process in requirements specification is the translation of customer and stakeholder capability desires into engineering goals. In most cases, the ideal capability cannot be reached, and thus requirements specification should also indicate how to trade among the capabilities. Concept generation and selection can be performed in a qualitative setting, typically in the earliest stages, and becomes progressively more quantitative in the latter stages of conceptual design.

In the first two sections of this chapter, an illustrative review of the literature pertaining to the stages of conceptual design is presented. The sections are divided between the requirements specification stage and the concept evaluation and selection stage. Generalized approaches are presented in addition to GA specific application of methods. Along the way, commentary is given pertaining to how the characteristics of the existing approaches differ in comparison to characteristics of an idealized approach. Most notably, these ideal characteristics include the ability to perform rigorous and objective comparisons of many solution concepts, dynamically address interactions between capability desires and engineering solutions, and to drive the design process based on the ability of a solution to satisfy desired capabilities.

The third section of this chapter is focused on travel demand analysis, specifically those that are centered around GA. This is a recently developed field of research which explores the sensitivity of GA system attributes to the distribution of demand among travel markets.

These analysis methods are noted to have the capability of bringing an analytical perspective to the requirements specification process, although further development is necessary.

The chapter concludes with a summary of the literature review, specifically a summary of the differences between the existing approaches, individually and as a whole, and the idealized approach. This summary review leads to the motivational and methodological research questions and hypotheses which drive this research.

2.1 Requirements Specification Methods

The goal of requirements specification is to transform the capabilities of the product, as desired by the customers and stakeholders, into a set of product specific requirements. In the traditional sense of aircraft design, a set of mission performance goals and a budget was typically brought forth in a request for proposal, and the design process focused on the achievement of said performance. Under new design paradigms (see Appendix B), the declaration of requirements has become increasingly open-ended, such that the requirements synthesis process has become a more integral part of the vehicle design process.

In this section, three tools associated with the requirements specification stage are presented: market survey, Quality Function Deployment (QFD), and the Unified Tradeoff Environment (UTE). These tools are illustrative of those available for use in the requirements specification stages. The market survey - a necessary tool in the industrial setting - is a process for gathering capability information directly from the customers and stakeholders in the existing markets. This information can then be organized in a qualitative problem specification process, such as QFD, which puts ranking on the importance of requirements, metrics, and constraints. When aircraft specific analysis models are available, a more quantitative process, such as UTE can be implemented to similarly identify and consider tradeoffs among the most important requirements, metrics, and constraints - through a graphical representation. In some settings, especially non-industry, the market survey may not be available or feasible, and thus the latter methods must be used with some amount of subjective input.

2.1.1 Market Survey

A market survey consists of gathering information about the current markets, and translating the results into meaningful conclusions that help to define a new market or a new solution to an existing market. This process involves talking to the customers and stakeholders concerning the desired capabilities, and concurrently surveying the existing set of available solutions.

In order to maintain or gain position in the market, industry entities talk with the customers, through discussion groups or formal survey questions, in an attempt to understand how their capability desires may be evolving and if this constitutes the need to modify the existing designs and possibly create a new market. Surveys performed in an industry setting will focus on specific markets, and likely include questions which have been formulated with certain possible design directions in mind.

In an evolutionary design setting, this is a highly effective, albeit time consuming and potentially costly process. In the consideration of future systems - which might entail a large number of revolutionary solutions and which may interact with other necessary systems that are not yet existing - it may be difficult to create a survey which can bring forth dependable conclusions. This is because there is an amount of uncertainty and subjectivity when asking for opinions concerning unfamiliar systems, as well as a limit to the number of questions that can be answered withstanding human concentration (discussed further under QFD). In consideration of academic and policy planning researchers, these surveys will likely remain proprietary to the industry. Some public surveys exist, including the 1995 American Travel Survey (BTS, 1997) and the General Aviation and Air Taxi Activity Survey (FAA, n.d.). These surveys are broad in scope, and mainly summarize how existing aircraft owners use their aircraft, without indication about what might be done differently.

In addition to talking to the customers, it is important to survey what solutions exist and how they perform or might apply to the market. In 2002, The Boeing company performed a study entitled Dual-Mode Air Transportation Systems, or DARTS (Cummings and Hoisington, 2002). An extensive survey of weight and handling aspects of automobiles combined with qualitative analysis of stowable wing geometries provided a basis for concept

generation and development for a new dual-mode vehicle market. Subsequently, analysis environments were built for tradeoffs of vehicle performance requirements including payload, range, and “level of roadability”. Some results from this study are presented in Figure 8, including an estimation of the weight breakdown of solutions ranging from the extreme ends of the dual-mode aspects - helicopter to automobile - as well as estimated payload-weight tradeoffs of the solutions. In this example, the jump in weight fraction through inclusion of the 4 street wheels with steering indicates a significant obstacle to overcome.

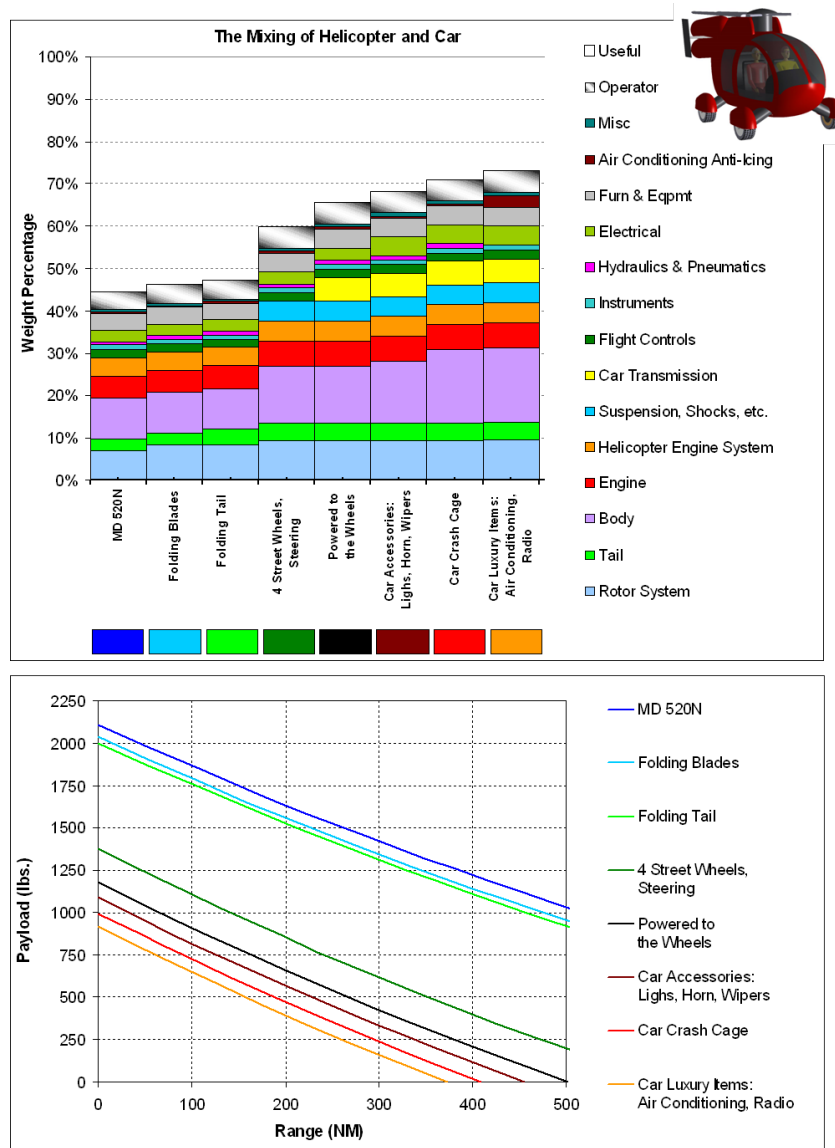


Figure 8: DARTS sample trade study (Cummings and Hoisington, 2002).

Roskam (2000) derives a solution for a regional jet transport in a similar manner. Through a series of qualitative and quantitative market assessments and examination of existing solutions, he suggests a solution for a new market - the 10-22 passenger regional transport. After identifying that the cost of the aircraft itself will be the major issue in achieving a solution to this market, single and dual fuselage solutions - whose production lines share many interchangeable parts - are presented.

The two previous examples focus on the solutions of the existing market in the survey. This type of study is important in the identification of possible solutions, but in general does not constitute a rigorous methodology for comparing a large number of possible solution concepts.

2.1.2 Quality Function Deployment

The Quality Function Deployment (QFD) process, is a standardized means of translating customer desires to the design process by creating a rigorous product specification (Terninko, 1996). The central QFD tool is the House of Quality (HOQ), an example of which is displayed in Figure 9, which connects the concerns of the customer, found through survey or otherwise, to the concerns of the engineer, eventually to vehicle specific requirements, culminating in a set of “importance weightings” for various vehicle objectives. The HOQ organizes the relations and interrelations between the customer desires and the engineering concerns in a set of three matrices, which the engineers and decision makers jointly fill in. Finally, the customer-engineering relation matrix, along with weightings of each customer desire, are utilized to create “importance weightings” for each of the engineering concerns. Sometimes this process is cascaded into a subsequent HOQ for translation to further subsystems.

While QFD, and similar subjective requirements synthesis tools, have strengths in rigorously organizing the relations between the “voice of the customer” and the engineering concerns, they must be used with caution. A benefit of the QFD process is the organizational understanding gained by the engineers and decision makers as they fill in the matrices.

Although the resultant “importance weightings” can help to separate the very important from the very unimportant engineering concerns, the numerical meaning has not been shown

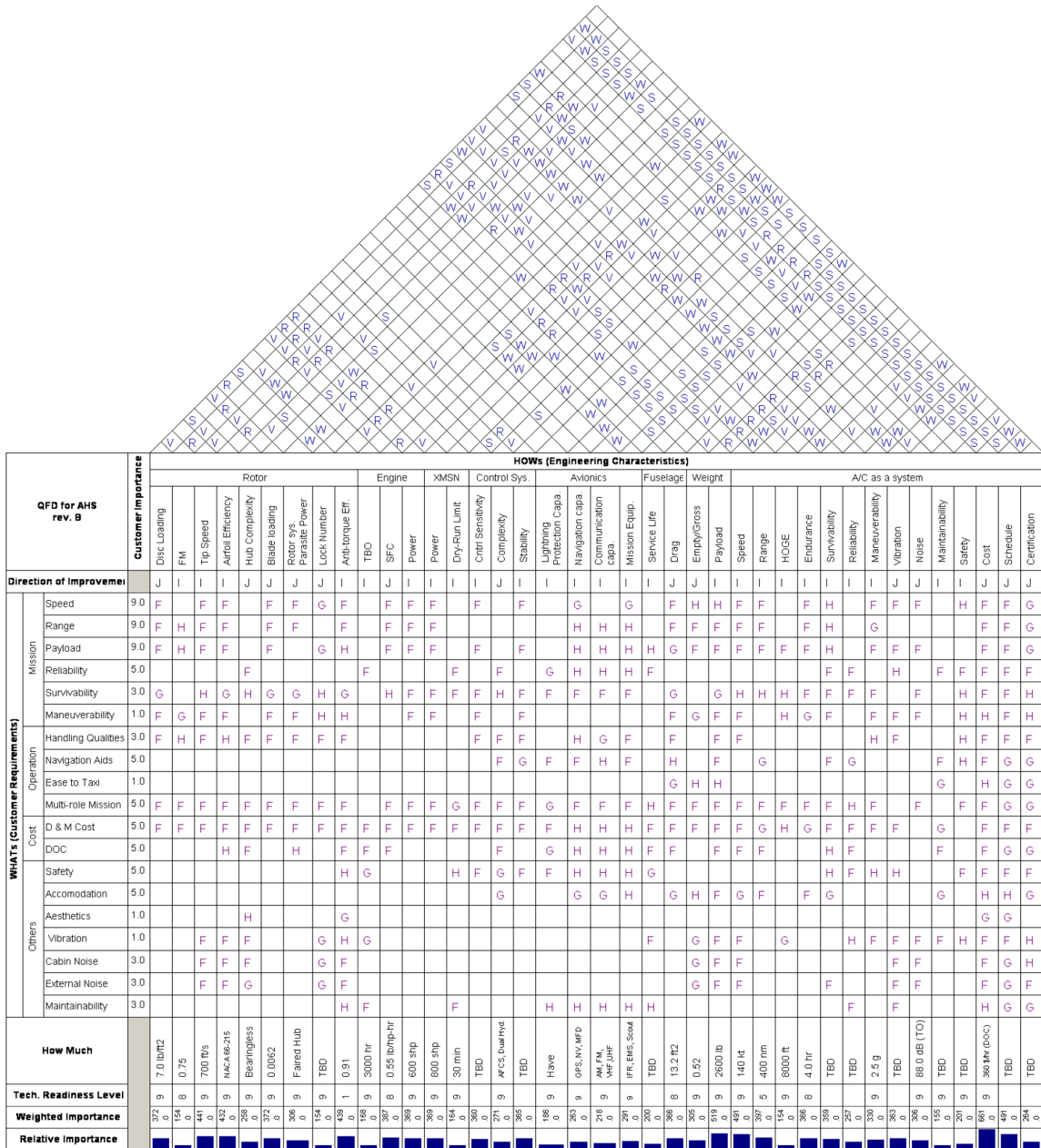


Figure 9: Notional PAV “House of Quality”.

to be accurately applicable to quantitative design processes. Actually, Arrow (1963) proved that there is no survey method for requirements elicitation that can satisfy a set of properties that ensure the trustworthiness of operating on the results of the survey, for the sake of product specification or selection. Hazelrigg brings forth some examples of this phenomenon in the process of QFD and similar methods (Hazelrigg, 2003). He further states that without pair-wise comparison of all design alternatives in consideration, selection is uncertain. Additionally, double-booking and dis-regard of scale are typically common mistakes that result in arbitrary “importance weightings”. Double-booking (having multiple customer desires that boil down to the same thing) result in overemphasis of certain engineering requirements. Additionally, the scale of the customer and engineer characteristics are not included, thus an engineering objective may be over-emphasized, even though it is the most easily satisfied by all designs.

2.1.3 Unified Tradeoff Environment

The idea behind the Unified Tradeoff Environment (UTE) is to combine the quantitative, parametric effects of design, requirements, and technologies into common visualization and analysis environments, making requirements elicitation an integral part of the vehicle design process. The UTE, first discussed by Mavris and DeLaurentis (2000), was sought out because “... understanding the simultaneous impact of requirements, product design variables, and emerging technologies during the concept formulation and development stages is critically important, and until now elusive.”

The concept was further elaborated by Baker, culminating in his thesis, in which requirements, design, and technology effects were combined to form a unified conceptual design environment for a commercial tiltrotor application (Mavris et al., 2000; Baker and Mavris, 2001; Baker, 2002). The process of creating and building a UTE is summarized here:

1. Identify the baseline vehicle and mission.
2. Identify parametric quantification of design, technology into a variable set, and determine the ranges over which they should be modeled.
3. Mission space model: Either through aggregating multiple missions or through given requirement ranges, identify requirement variables and ranges over which they should be modeled.

4. Model the baseline in the analysis code(s).
5. For each set of variables (design/uncertainty, technology, requirement), run a DOE and create a RSE that models the difference in responses from the baseline.
6. Aggregate the separate RSEs by adding them to the baseline responses to create the UTE.

The immediate benefit of building a UTE is the ability view of the simultaneous and parametric effects of all variables in a common visualization, such as a prediction profiler - a matrix of plots where the variation of each variable, indicated on the x-axes, is mapped to its effect on each metric, indicated on the y-axes, while all other variables are held constant. In a GA specific example, Ahn et al. (2002) built a UTE for each of two alternative rotorcraft: the Robinson R22/R44 and the Groen Brother Hawk4. This allowed them to simultaneously consider the impact of technology variables and requirements variables in the PAV problem, as for example seen in Figure beginning 10.

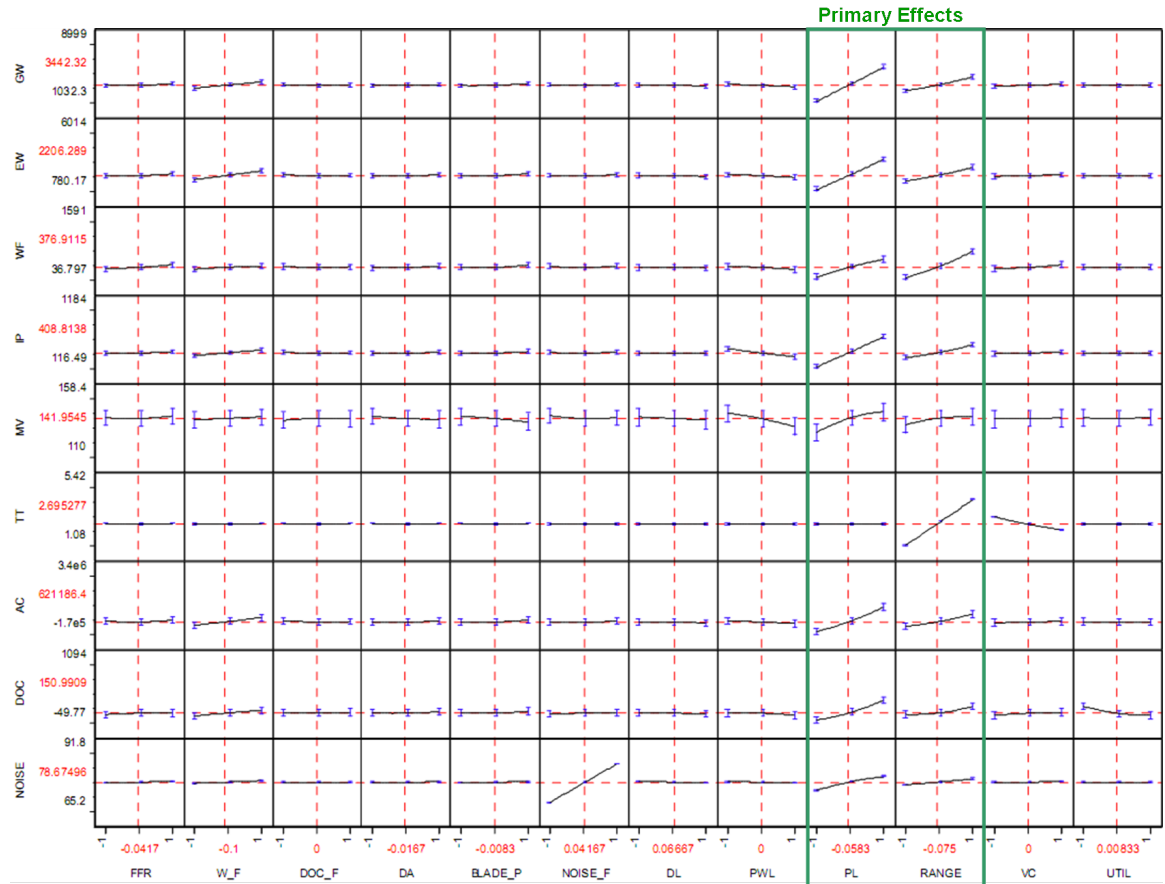


Figure 10: UTE example visualization (Ahn et al., 2002).

UTE visualization can be a useful tool in discovering the relative strengths - that is their effects on metrics of interest - of requirements, technologies, and design variables in the problem. To its disadvantage, it tends to have the inherent problem of masking important variables because of inherent differences in how design, technologies, and requirements impact the metrics. In Figure 10, for example, upon close study it is apparent that the aircraft range (RANGE) and payload (PL) variables dominate the the remaining variables' effects - including the fuel flow reduction (FFR) and direct operating cost reduction (DOC_F) factors - on the metrics. It is even apparent that the sensitivity of most other variables falls within the uncertainty of the metamodel fit.

Additionally, the typical problem dimensionality is large. In his thesis, Baker applied the UTE to the Future Transport Rotorcraft (FTR) problem. The final UTE consisted of 29 input variables and 10 output responses. Having a large number of variables makes the process of examining the UTE through visualization difficult. The UTE depicted in Figure 10 for example had only 12 variable inputs and 9 output metrics, and is also a static representation - each variable is varied independently while the others are held at the value indicated by the red hairline. To overcome this problem, a quantitative decision-making technique must be implemented - discussed in the following section.

2.2 Concept Evaluation and Selection Methods

After the problem has been defined through requirements specification, conceptual design moves toward the evaluation and selection of likely solutions. Conceptual design is an iterative process, and hence this stage has quantitative as well as qualitative tools available to account for the early stages, when quantitative models might not be available. A concept might also be represented by an alternative. For the purposes of this thesis definitions for concept and alternative by Mattson and Messac (2003) are used:

Design Concept: An idea that has evolved to the point that there is a parametric model that represents the performance of the family of design alternatives that belong to the concept's definition.

Design Alternative: A specific design resulting from the unique parameter values used in

the parametric model of a concept.

Concept selection can refer to both the selection of concepts and the selection of alternatives, dependent on the type of information available.

Concept selection also implies that a set of concepts under consideration have been generated. The method for concept generation could produce just a few alternatives, such as with a “round table” discussion, or millions of concepts, through the combinatorial of subsystem alternatives, as in the morphological analysis (Zwicky, 1969). A survey of available literature may also lead to a list of concepts which have been considered for aspects of feasibility.

Both qualitative and quantitative concept selection methods exist. In either case, especially qualitative methods, caution should be used to ensure that all concepts are being compared on a fair “apples-to-apples” basis. The reader is referred to Hazelrigg (2003) for an excellent summary of selection methods, and the caveats that should be taken with each. Hazelrigg also provides a list of favorable properties for concept selection methods, repeated here, but explained in detail in the paper:

1. The method should provide a rank of ordering of candidate designs.
2. The method should not impose preferences on the designer, that is, the alternatives should be ranked in accordance with the preferences of the designer.
3. The method should permit the comparison of design alternatives under conditions of uncertainty and with risky outcomes, including variability in manufacture, materials, etc., which pervade all of engineering design.
4. The method should be independent of the discipline of engineering and manufacture for the product or system in question.
5. If the method recommends design alternative A when compared to the set of alternatives $S=\{B,C,D,\dots\}$, then it should also recommend A when compared to any reduced set SR, such as $\{C,D,\dots\}$ or $\{B,D,\dots\}$ or $\{D,\dots\}$, etc.
6. The method should make the same recommendation regardless of the order in which the design alternatives are considered.
7. The method itself should not impose constraints on the design or the design process.
8. The method should be such that the addition of a new design alternative should not make existing alternatives appear less favorable.

9. The method should be such that obtaining clairvoyance on any uncertainty with respect to any alternative must not make the decision situation less attractive (information is always beneficial [to an alternative's score]).
10. The method should be self-consistent and logical, that is, it should not contradict itself and it should make maximum use of available information for design alternative selection.

2.2.1 Qualitative Evaluation and Selection

In the earliest stages of conceptual design, when little quantitative information exists, a qualitative selection method might be used. One might also be used to consider the selection among concepts for which features are not easily measured by numerical means - comfort, safety, aesthetic appeal.

A prominent method is the Pugh selection method. The Pugh method involves qualitatively comparing a group of alternative solutions to a datum concept based on a set of determined criteria (Pugh, 1996). The process is often coupled with the QFD process, which assists in determining the concepts and the judging criteria, and results in a ranking of alternatives. The primary steps include choosing the evaluation criteria, formulating the decision matrix, choosing and clarifying the alternative concepts, choosing a datum concept and then running and rerunning the decision matrix (Clausing, 1994). In the end the design team receives an analysis of whether each concept is better than, poorer than, or about the same as the datum concept.

As mentioned, in general qualitative selection methods are used in the early stages, when very little information is available. Various methods are available, dependent upon the level of information available, and include the analytical hierarchy process, or AHP (Saaty, 1980), and the Technique for Ordered Preference by Similarity to the Ideal Solution, or TOPSIS (Hwang and Yoon, 1981), but these methods do not apply well to latter stages. Furthermore, their implementation is as much as an exercise of organization of the existing information as a selection method - the results are dependent on subjective evaluation.

2.2.2 Quantitative Evaluation and Selection

Methods for quantitative evaluation and selection among design concepts in general couple the numerical models of the aircraft with a technique for decision making. The aircraft models are problem dependent, and as long as the desired metrics are properly represent, are not the subject of discussion. The generalized goal of the decision making technique within the quantitative selection setting is choosing the design variables, requirements, and metrics that are best for the specified problem. An important intermediary to this process is the selection of an alternative within each concept space that best represents the concept - often an optimization process. For either of these steps, objectives must be defined which guide the process. In this section, several quantitative evaluation and selection methods are presented which handle the objectives in different manners.

2.2.2.1 Objective Aggregation

A common practice in aircraft design is to use the gross weight as the ultimate success metric. For example, Holmes (1980) and Crispin (1992, 1994) investigate optimization techniques by minimizing the gross weight under a fixed set of mission requirements and constraints on the takeoff and landing performance. Beyond demonstrating the success of optimization, Holmes showed that the process can bring forth information that relates to the design of requirements for GA aircraft. Specifically, he notes that the FAA stall speed requirement is the primary detriment to achieving an unconstrained optima. In general though, it cannot be expected that all problems can be solved through the optimization of a single objective.

The most basic solution is to aggregate objectives into a single objective. Many forms of aggregation have been used in the past. For example, Levine et al. (2003) create a combined physics and empirical based parametric engine cycle and sizing representation of a light GA aircraft with two different engines: gas turbine and a ducted fan-piston combination. They then created a scalar overall evaluation criteria (OEC) function, a linear combination of engine horsepower and aircraft weight, each scaled by a weighting parameter. A gradient-based optimization algorithm was used to optimize the engine cycle to reduce the OEC function, while sizing the engine and aircraft for a specified mission.

The aggregation of objectives provides a convenient solution to concept evaluation and selection because it makes each alternative immediately comparable to the other alternatives, and thus a scalar ranking of alternatives can be created. The problem though lies in the creation of the aggregate objective - in general it is a subjectively created form. In some specific cases, an aggregate objective may be time proven to show that it alone is a trustworthy measure of ultimate comparison of alternatives, but in general there is no objective guarantee that it is a fair measure of comparison.

2.2.2.2 Pareto Optimization

A design point within a given set, each represented by a vector of selected objectives is considered Pareto optimal if there is no other point in the set for which all objectives can be considered better. If such a point existed, it would be said to be Pareto dominant with respect to the other point. The subset of Pareto optimal points is termed as the Pareto frontier. Figure 11 displays a representative multi-variate plot of a five objective Pareto front from Buonanno (2005), where, for example, a prominent trade can be seen between objectives 1 and 2.

Resolution of a Pareto frontier through optimization is a purely numerical process, although selecting an alternative or ranking alternatives along the frontier is not. In specialized cases, one concept can be said to dominate another concept - that is for each point on one concept's frontier there is a point on the other's which is Pareto dominant - but in general this cannot be guaranteed. Visualization of the frontier can provide an environment for tradeoff exercises, but as dimensionality grows, a distinct frontier is not present, as seen above. Additionally, the tradeoffs again rely on the knowing exactly how tradeoffs should be made - a matter of customer preference and stakeholder capabilities.

2.2.2.3 Joint Probability Distribution Decision Making (JPDM)

The Joint Probability Distribution Decision Making (JPDM) technique represents one concept selection method that could be considered to fall into the robust concept selection category. Robust concept selection indicates that designs must be both favorable towards

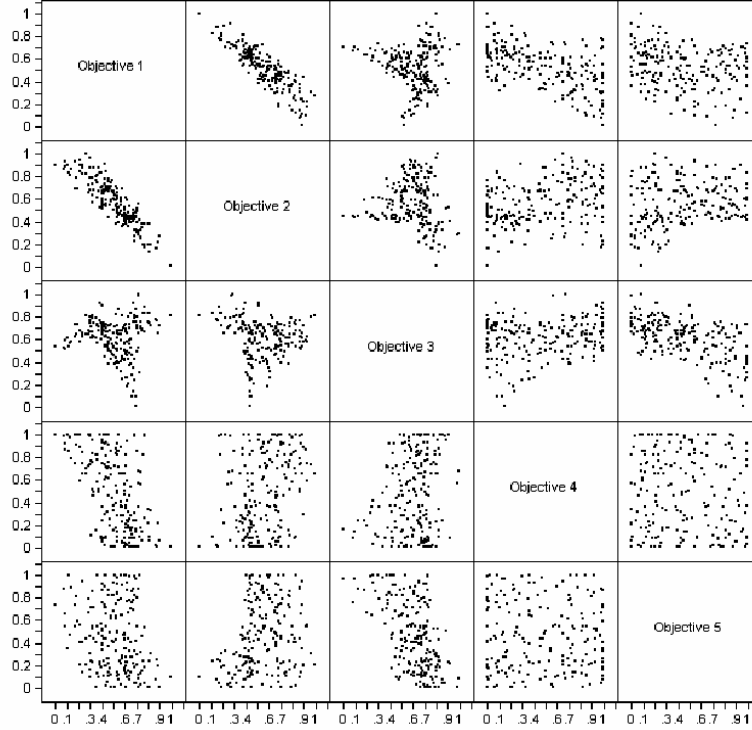


Figure 11: A set of Pareto optimal designs shown by multi-variate plot .

objectives, and simultaneously attempt to minimize the variation of those favorable characteristics when future processes and conditions have some associated uncertainty. An excellent example, where manufacturing tolerance uncertainties are applied to turbine blade design for robust performance is found in Kumar et al. (2007). The goal is to not only optimize the deterministic value of objectives, but also to ensure that similar and acceptable performance will result if the future is not as we nominally expected.

The first step of JPDM is to define distributions - e.g. normal, triangular, uniform - to known noise variables - those which are not under direct control and may take various future values - rather than nominal or “worst-case” values. Next, the distributions are propagated through the design analysis using Monte Carlo Simulation (MCS). In MCS, a large number of runs is performed by randomly pulling input vector values from the noise distributions. The resulting output distribution is called the joint probability distribution (JPD), as illustrated in Figure 12 from Ang and Tang (1984).

The JPD represents the distribution of results that might be expected for a fixed design

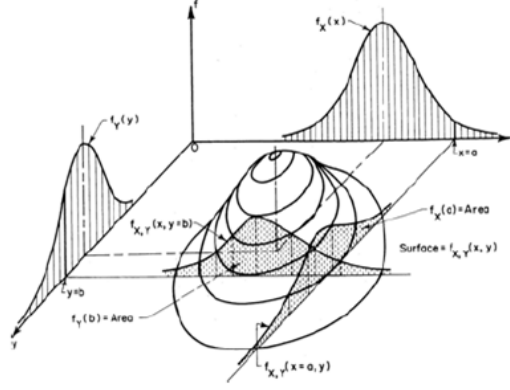


Figure 12: Illustrated joint probability distribution.

under distributions of uncertainties. The probability of success (POS) is found by integrating the output distribution between acceptable objective values. This could be used in an optimization problem then becomes to vary the design such that it maximizes the POS. Once each design concept has been optimized, the resulting alternatives can be ranked based on their POS.

Li has applied JPDM to the evaluation and selection of PAV concepts (Li and Mavris, 2003, 2004; Li, 2007). The metrics which constitute the POS calculation were noise, direct operating cost, and door-to-destination time. The concepts are ranked by the POS of meeting all these metrics simultaneously, as depicted in Figure 13.

The JPDM methodology is an interesting method for the selection of alternatives, and intuitively solves the multi-objective nature of most problems. The key to successful implementation though is the accurate and full representation of all objectives by which the POS is calculated. If any of these objectives are not properly defined, that is their acceptable level of success, or if objectives are left out, then the method is likely to produce arbitrary results. These problems are inherent to any design problem, but emphasize the importance of the requirements specification stage.

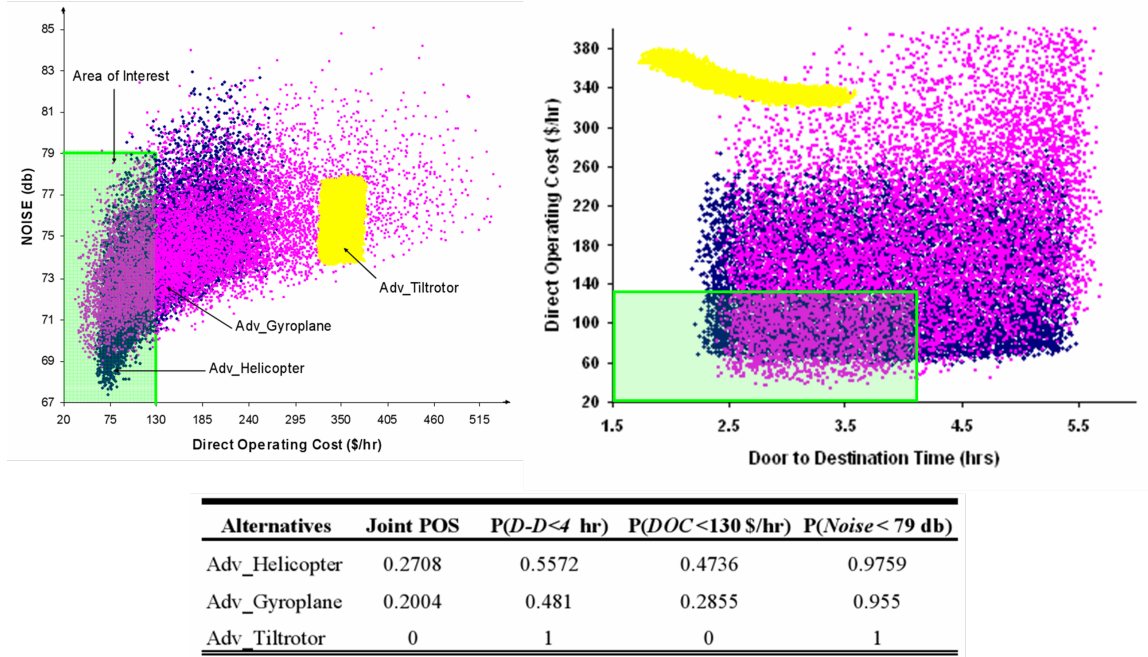


Figure 13: Probability of success selection example (Li and Mavris, 2003).

2.3 General Aviation Demand Analysis

General aviation design aspects differ from many other aircraft in the respect that the customers are numerous and diverse. This has made understanding the behavior - and furthermore the aggregate behavior - of these customers a subject of many researchers. This section briefly covers this research in an attempt to understand how these studies might be applicable to the problems associated with requirements specification found in the conceptual design literature.

As early as 1969, when a rise in GA usage was expected, Drake et al. (1969) attempted to quantify the mode choice process of hypothetical travelers. The primary effects of the choice process, and those most quantifiable, are time and cost. These metrics, which for a given trip definition are dependent primarily on the travel mode, are made compatible through definition of time value, which is traveler dependent. The aggregate value, termed by Drake as the “total cost”, is similar to the notion of utility - the inverse or negative of “total cost”. With this model, prediction of mode choice is made by selecting the mode with the smallest “total cost”. As seen in Figure 14, the model can be used to create a mode choice diagram,

that is a mapping of the mode selection to the trip distance and the traveler's time value. This concept of mode choice modeling is at the core of the demand-centric approach.

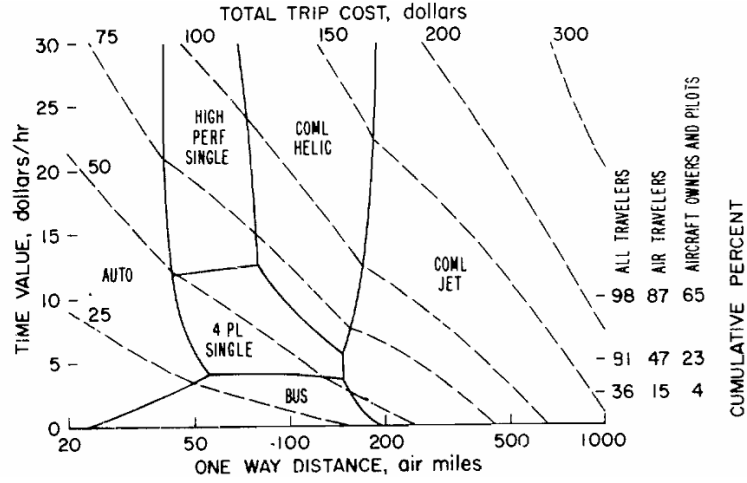


Figure 14: Traveler's mode choice diagram from Drake et al. (1969).

DeLaurentis et al. (2002, 2004) utilized the measures of time and cost in a method to estimate the long term viability of owning a PAV. The model calculates the cash flow over a given time period, or determines the breakeven point, and the user is allowed to adjust assumptions about the PAV performance and cost aspects, as well as numerous assumptions about the travelers annual utilization, length of ownership, and the aircraft system costs.

The two previous studies provide insight into how an individual traveler might make travel or purchase choices. On the other hand, they do not represent the behavior of a population of diverse consumers - such as within the US - and they tend to pre-specify the characteristics and behavior of the users through a number of assumptions. The proceeding models, developed within the last five years, apply similar concepts, but instead across a large scale simulation of travelers. These travelers, whose fundamental representation varies by model, can to determine through mechanical and historical models the time and cost characteristics of their travel and how they might choose among their travel options based upon a distribution of characteristics that represent the US population.

The Transportation System Analysis Model (TSAM) was developed to study the potential impact of a notional Small Air Transportation System (SATS) architecture on the

National Transportation System (NTS) (Baik and Trani, 2003; Trani, Baik, Hinze, Ashiabor, Viken and Neitzke, 2005; Viken et al., 2006). This program predicted the modal split on the county level, with a GA mode as an alternative. The county level information is aggregated and then redistributed to airports to determine the airport enplanement demand and flight paths. The prediction of air traffic impacts was of key importance in its development, as emphasized by the databases depicted in Figure 15.

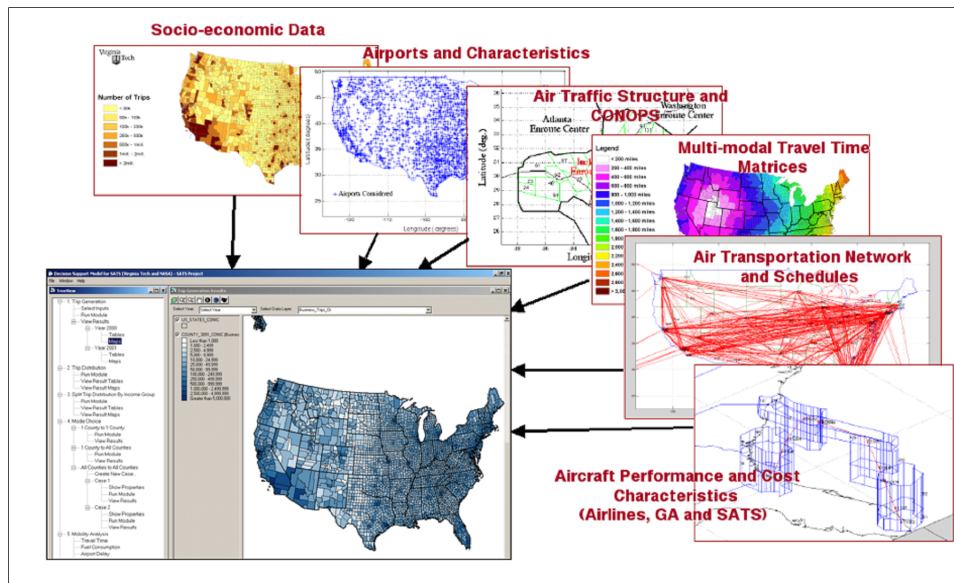


Figure 15: Transportation System Analysis Model databases.

In one study, TSAM was integrated with a detailed air-taxi scheduling routine, the Monte Carlo network simulation model (MCATS), to determine the feasibility of supplying the service (Seshandri et al., 2006). This study constitutes one of the few efforts to capture the effects of contributing systems on actually capturing demand - without assuming that the predicted demand will automatically be captured. The study covers several interesting interactions, but does not consider how the aircraft system - changes in design - might come into play. In another study, Trani, Baik, Hinze, Ashiabor, Viken and Cooke (2005) suggested integration of preliminary aircraft analysis to the TSAM model. The focus is to capture the effects of off-design performance, rather than changes to vehicle design. Additionally, the feasibility and viability concerns of the service provider are assumed to be captured, as well as the viability of the aircraft manufacturer. While these two studies recognize

the importance of capturing the interactions among systems, they remain focused on very specific aspects within these interactions, rather than the system of systems as a whole.

The code *Mi* was also developed to capture the large scale effects of demand sensitivity to modal attributes (Lewe et al., 2002; DeLaurentis et al., 2003; Lewe et al., 2003; Lewe, 2005; Lewe et al., 2006). *Mi* is fundamentally different from TSAM in that it represents the US as a set of abstracted locations - large, medium, small, and non-metro - and furthermore the basis for modal distribution prediction lies in the decisions of a population of simulated consumers, or agents. Each agent is generated with a set of attributes, including household income, household size, locale type, licensing, and travel purposes. Having a list of desired travel (represented by each block in Figure 16), each agent proceeds through a series of choices where it is determined which trips will be taken (bounded by a “mobility budget space”, i.e. time and cost budgets), and what mode of travel is used. The model also represents the GA mode by a number of system level attributes including performance (range, speed, payload) and cost (operating rate).

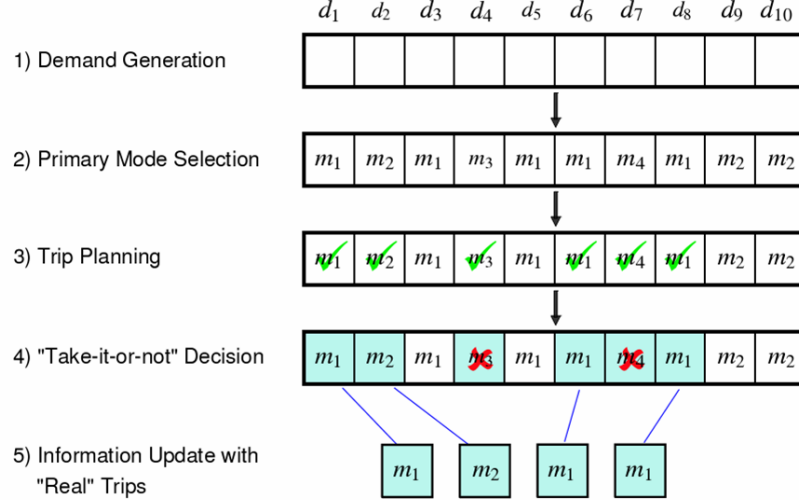


Figure 16: Agent's travel mode selection process.

As will be discussed later, the prediction of modal distribution through the agent decision making process gives *Mi* a significant amount of predictive power in relation to the consumer-aircraft interaction. Whereas in TSAM, the modal distribution is done in bulk on the county

level, Mi agents make decisions individually, and over a number of simulated trips, giving a greater capability to bring out the emergent behavior of the consumer population.

Example results from Mi are shown in Figure 17, where the choices of the entire agent population has been plotted with respect to their income and trip length. Notice that this representation can be compared to the mode choice diagram of Drake, Figure 14, but with some clear differences. Drake’s diagram has discrete mode choice regions with distinct boundaries. The Mi results have regions of mode dominance, but the boundaries are fuzzy, for several reasons. First, Drake’s model can be thought of as a single agent, defined only by their value of time. Mi ’s population of agents are defined in greater detail, including their household size, locale type (affecting travel time), and of course income. Second, Mi agents make mode choice selections in a probabilistic, not deterministic manner. Whereas in Drake’s model the selected mode is the lowest “total cost” mode, in Mi , each mode’s probability of being selected increases as its “total cost” decreases.



Figure 17: Sample Mi results: mode choice by trip length (x, km) and income (y, \$).

As a “block box” the price-demand, or p-D diagram is a useful representation. In this diagram, the demand generated by the agent population is aggregated (D) and plotted against a price index (p), for various attribute assumptions, as in Figure 18. This representation hints at the capability of a demand analysis model to aid in the design process, as in this

example the sensitivity impacts from design changes or cost changes - albeit assumed as independently variable - are translated to the predicted demand.

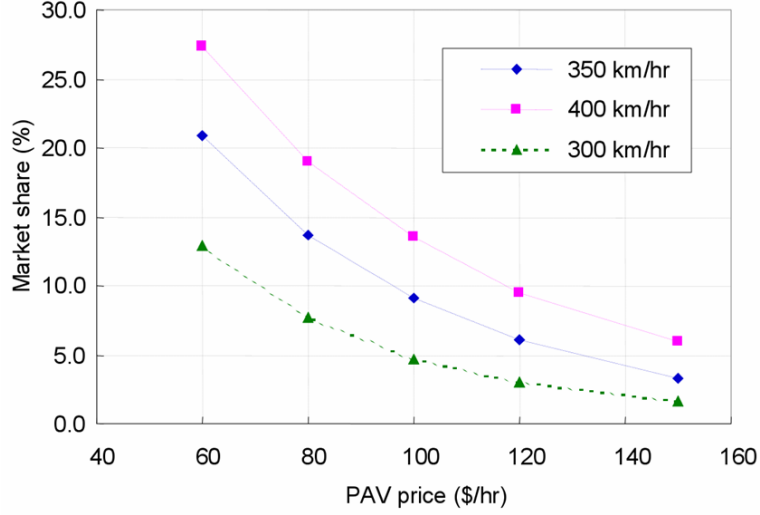


Figure 18: Sample *Mi* results: price-demand (p-D) curve, with sensitivity to flight speed.

To date, the use of *Mi* has not been demonstrated in concert with service provider or aircraft system models. Thus Figure 18 shows that a lower rental price and higher speed attracts more demand, an expected result when considering these as independent attributes rather than dependent upon one another and upon other systems. It is known that the rental price is affected by the performance level of the vehicle (e.g. a high speed aircraft is more expensive to own and operate), as well as the mode of operation by a service provider. In summary, demand models provide an important capability for the goals of this thesis, but on their own, *Mi* and other models make assumptions that the mode is feasible, viable, and available to the consumers as described by the input attributes.

2.4 *Synopsis of Literature Review*

The literature review began with a *vehicle-centric*, conceptual design aspect. Several examples demonstrated typical methods of approach to the conceptual design problem, specifically as applied to GA. At the core of each is a process that combines physics and empirical lessons of the past to quantitatively assess the feasibility of reaching a set of requirements, and an estimate of cost goals. An important part of this analysis - what makes the solutions relevant

- is determination of the design requirements, and the ability to make multi-objective trade-off decisions. The connection between these processes is often through a manual iteration, as depicted in Figure 19.

Knowledge of design requirements is dependent on the problem at hand. Many of the design examples were geared toward a high-level objective, e.g. “design a personal air vehicle that will enhance the nation’s mobility”. This is problematic to the requirement definition and metric tradeoff processes.

Decision making tools based on qualitative mappings, e.g. QFD’s House of Quality, do enhance the organization of information, and bring forward the most important metrics. But, as Hazelrigg (2003) indicates, qualitative analysis cannot be used to accurately predict the choice of customers, without first asking them to make pair-wise comparisons about all possible alternatives. Since conceptual design considers a large number of variables, some discrete and some continuous, this task is not possible. This problem can also be restated as the inability to put accurate numerical values on requirements, metrics, and constraints, without prior knowledge of what the values should be.

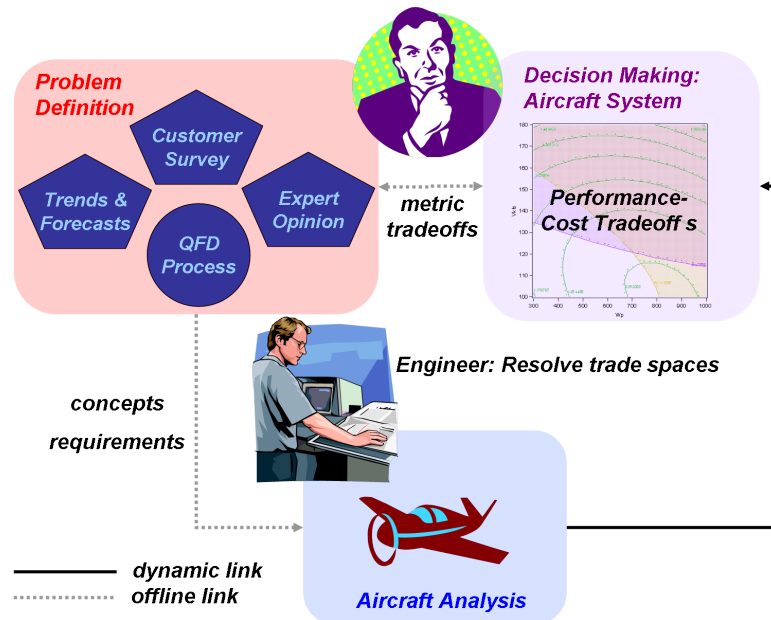


Figure 19: The conventional conceptual design process.

Additionally, to make selections, the problem must also be stated in full. In the personal

air vehicle problem, for example, each design may attract a different consumer base, and require different operational procedures and business models to pursue. To exemplify these arguments, the research by Li and Mavris (2003), represented earlier in Figure 13, is studied more closely. In his study, the value by which a given metric was deemed as acceptable was predetermined, allowing demonstration of the numerical selection process. But, the determination of these values is likely to add a level of bias or arbitrariness to the process. First, if the acceptability values are determined through a process such as QFD, then some amount of subjectivity likely went into determination of the values. Secondly, metrics do not necessarily translate well from one concept or market to another. For example, the selection process eliminated the tiltrotor concept. But, the tiltrotor, which would likely carry a larger number of passengers, fly much faster, and be operated by an on-demand service provider, was compared under a common set of metrics as smaller, cheaper aircraft, more likely to be chartered or privately operated. Not only is the customer base different, but the metric is arbitrary because although one alternative costs more per hour, it may also be flying at a significantly faster speed. The point here is not to single out this particular research, but rather illuminate common problems that are faced when designing such a system.

As a more generalized example, a hypothetical design scenario has been created to exemplify problems in the metric tradeoff process. As displayed in Figure 20, part of the requirements space (design speed, V_{kts} , and payload, W_p) for a single engine piston has been mapped to the resultant costs associated to the aircraft acquisition (ACQ) and operation (DOC), as well as an OEC to be minimized ($OEC = \frac{ACQ \cdot DOC}{V_{kts} \cdot R \cdot W_p}$). This OEC represents a cost to benefit ratio, but any OEC could be used for the sake of argument. Contours of constant ACQ (gold) and DOC (purple) have been created which represent the costs of today's aircraft. Because the trades between costs and performance are not easily gained, this type of cost constrained design is often utilized. Next, OEC contours are plotted, and the problem becomes that of optimizing the OEC within the bounds of the plotted cost contours. A star indicates the point of constrained optimality by the definition of the problem given.

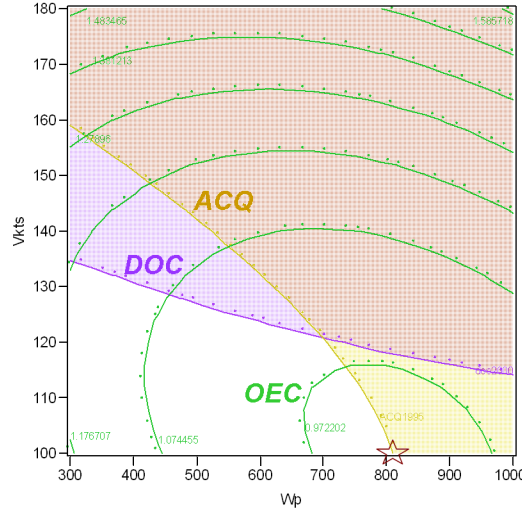


Figure 20: A hypothetical performance and cost tradeoff scenario.

While this is a hypothetical example, it draws out several problems in real design scenarios. First, setting constraints on *ACQ* and *DOC* eliminated a large portion of the design space. Because the future circumstances are not well known, the optimal design may actually be one which has a greater performance for which more consumers are willing to pay an increased price. Second, this *OEC*, or any aggregate objective function cannot be proven to truly represent the preference of the customer and the capabilities of the stakeholders.

In the case of industry, one might argue that the requirements, constraints, and objectives are well known. Years of experience and interaction with customers allows industry to adapt and build business cases for new designs, or evolve existing designs. This process is undoubtedly successful - industry has demonstrated viable production - and necessary. On the other hand, the process is time consuming and may inhibit exploring options - concepts, requirements, and markets - different from the current circumstances. Slow evolution of past success provides a foundation for a manufacturer, but a progressive search for new concepts and new markets should also have its part in the business.

As a summary of the design tools associated with the conventional conceptual design phase, one of the main problems is the determination of customer preferences, as well as the capability of the stakeholders. The latter comes about through iteration - presenting

potential designs - the capability of the stakeholder - to the customer for preference information. The pros and cons of the conventional conceptual design tools are highlighted, in Table 1 below, showing that the designers tools, the performance and cost analyses and the qualitative system mappings (e.g. QFD), all point towards the necessity to properly account for requirements and metric tradeoffs.

Table 1: Conventional design and problem definition methods summary.

▲pro ▼con • both

Analysis-Based Concept Selection	▲	Many models and methods exist
	•	Definition of requirements, constraints, and metrics are key to success
Qualitative Requirements Definition	▲	Organizes the available information
	▲	Brings forward important requirements, constraints, and metrics
	▼	Can not assign specific values to requirements, constraints, and metrics
Market Survey and Analysis	▲	Directly assess the consumers' desires and tradeoff preferences
	•	Have basis in an existing consumer population
	▼	Assumes a certain market structure and operational infrastructure
	▼	Time Consuming

Observation: The summary of conventional methods indicates a dilemma for the conceptual designer - dynamically assess alternatives, but with qualitative, imprecise information to guide them, or accurately assess alternatives, but with long times between iterations.

Undoubtedly, these methods, likely used in concert, have allowed the design of GA aircraft up to this point in time. But, it is the purpose of research to seek enhancements to these methods, thus leading to the motivational research question and hypothesis:

Motivational Research Question: How can conventional design methods be complemented to promote a more dynamic *and* objective design environment?

Motivational Hypothesis: A system of systems model can act as a surrogate problem definition process, and thus enable a transition from system level metrics

to architecture level metrics – those metrics that represent “capability” – which can dynamically guide the design engineer.

The “capability” metrics may be dependent on perspective, but generally lean towards the maximization of captured demand and profit. Thus, if a system of system model can tell the engineer how much usage a certain aircraft configuration can capture, the problem of vehicle system level metric tradeoffs becomes irrelevant. This capability - a fast, numerical assessment of “success” - would allow rapid exploration of alternatives. The problem now becomes how to synthesize and simulate the architecture and the relevant “success” metrics.

To this end, *demand-* and *operations-centric* research was reviewed in the second half of the literature review. This review provided a glimpse of the demonstrated capabilities that might be an aid in estimating capability metrics. Utility theory has been used to predict a consumer’s demand for travel, specifically how they choose among travel modes. More recent research has expanded the idea to populations of travelers, where models for demand generation and mode choice have been created to estimate travel behavior of a simulated US population. These studies were made under the assumption that the GA travel mode was feasibly and viably available at the given price.

To certain degrees, the GA problem has been studied from supply, demand, and operational perspectives, but the research has been limited to “one-system-at-a-time” analysis, and focus has remained on specific aspects. Additionally, other systems are represented as static assumptions, or as independent variations of system-level metrics. Researchers have indicated the importance of looking at the effects of systems interactions, but to this point there efforts have been focused on enhancing and studying the validity of their models.

To consider the difference between a single system approach, and a system of systems approach, two hypothetical p - D diagrams are displayed in Figure 21. The first is represented with price as an independent variable, and the resulting demand curve is thus similar to that found by *Mi* (e.g. see Figure 18). This curve represents the consumer population, which creates demand, as a single system. The second curve assumes that the price is representative of the aircraft’s performance, and that the availability of a service provider is affected by the demand - they cannot viably operate in areas of sparse, yet existent demand. This curve

represents a system of system interaction between the vehicle, demand, and service provider systems. The major difference is that the second curve has a distinct price where demand is maximum, indicating the price - and corresponding performance level - where product and consumer synergize. Any lower price, and the performance degradation exceeds its worth, and any higher price, and demand declines due to high price. On both tails of the curve, the service provider will also be less available - there is a critical level of demand needed for a service provider to exist.

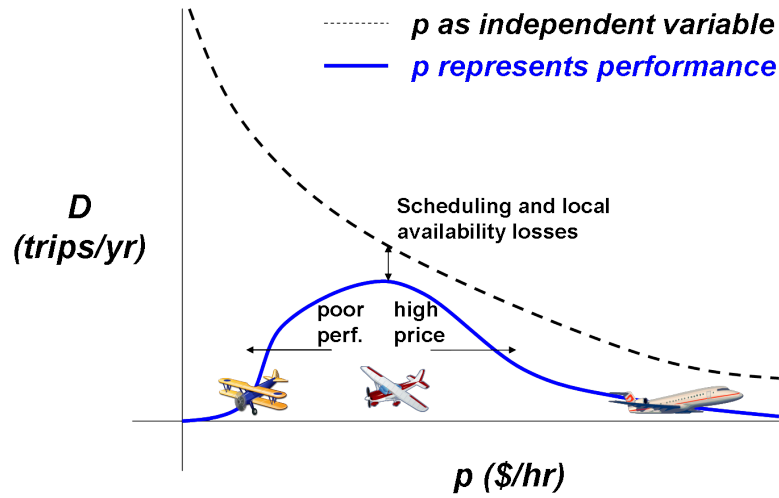


Figure 21: Hypothetical demand comparison: independent and dependent rental price.

This hypothetical comparison of single system and system of system perspectives leads to an important observation:

Observation: The interactions among systems cannot be ignored - the effect of other systems on the system of interest is need to seek a solution of maximum capability.

This key observation leads to the second research question and hypothesis:

Methodological Research Question: How can the system of systems model best represent the interactions of the contributing systems and thus lead to a design environment?

Methodological Hypothesis: By identifying and modeling the key feasibility and viability aspects of the contributing systems, major interactions can be unveiled which can lead to “capability” based design decisions.

This high-level hypothesis implies that a methodology can be devised in which the systems can be identified, synthesized into a system of systems model, and scenarios simulated such that a determination of “capability” can guide the process of system design. Prior to presentation of the methodology, a series of questions are pursued which, after the model is complete, can guide the exploration process and determine if the methodology and demonstrated implementation accomplishes what it was asked to do. These questions will be revisited following the presentation of results. These questions are summarized in the following supporting methodological research question.

Supporting Methodological Research Question: If the methodology is successfully implemented, what types of questions should the model be able to address?

Supporting Methodological Hypothesis:

- Can optimal requirements – those that maximize “capability” – be resolved?
- If so, how do these requirements:
 - Differentiate between markets?
 - Evolve with technology improvements?
- Where might inter-entity cooperation improve common objectives?
 - In the analytical sense, can synergistic solutions be achieved through the collaborative optimization of multiple systems?

Chapter III

METHODOLOGY AND IMPLEMENTATION

In response to the hypotheses presented, it is imperative that a methodology be established which formally addresses the development of the aforementioned system of systems, capability-based design environment. The methodology will also address the means by which the implemented environment is utilized to establish design decisions for future GA systems. The second half of this chapter will begin the implementation of the methodology. Throughout the methodology explanation, established planning tools and modeling perspectives are referenced, and further details can be found in Appendix B.

3.1 Methodology

The steps and details of the methodology are presented in the following pages. An overall flow diagram proceeds this description, and can be found in Figure 22. This diagram also indicates where these steps are implemented for the future GA problem within this thesis.

1. Problem Definition

Carefully establish the problem to be approached, first on a high level, and then see if it can be further specified. Careful organization of information can be key to saving time and costs down stream if the wrong problem is addressed. This information can be used downstream as well in consideration of concept down-selection and systems representation. The reader is lead to Dieter (2000) for a number of planning tools, including the seven management and planning tools, which can make the process efficient and rigorous.

2. Definition of capability metrics

A capability can be defined as the general potential or wherewithal to deal effectively not just with a well-defined single problem, but with a host of potential challenges and circumstances

(Davis, 2002). In general, consider how resources and processes are designed and organized towards achieving an overarching capability. Achieving that capability necessitates satisfying end-users and stakeholders alike. Consider all capability metrics, then consider, from a capability-based, system of systems perspective, what are the ultimate capabilities. For example, the desired capabilities of the aircraft end-user are important, but if viably captured demand is addressed the former become intermediate metrics.

Webb provides a concise set of analytical principals to consider when initiating a capabilities-based approach, listed below (from Webb (2006), abridged). These principals can be considered when determining the capability metrics, and also within the other steps of the methodology. Because some of these aspects will be considered further downstream, for example principal four, the problem definition and bounding phase will likely be part of an iterative process.

- Focus on outcomes (desired operational effects) of the enterprise end-user.
- Frame a portfolio perspective as a means of partitioning the problem and solution spaces in terms of capabilities.
- Approach issues holistically; consider a full range of alternative solutions to provide a capability.
- Examine the complex networks of inter dependencies, at different levels of hierarchical description
- Explicitly bound profound uncertainties attendant to complex adaptive system problems.
- Pursue an adaptive evolutionary approach to planning to position the enterprise to effectively respond to changes as they occur.
- Assess and balance the evolution of capabilities within the resource constraints for a wide range of diverse and stressing operational circumstances.

3. Systems representation - bound and down-select

The definitions of the capability-based design perspectives indicate that the effects of design changes are considered from a system of systems perspective. More specifically, the capability metrics are not directly measurable system metrics, rather they result from the

propagation of system metrics through other interacting systems. The first part of this step is to consider the entire system of systems for which the system of interest interacts - no matter how small the effect. This bounds the problem.

Next, consider how much effect each system has on the consequences of design changes - that is from a change in design variable, what systems have large degrees of interaction and relevant effect on the capability metrics. Creating system mappings, or cause and effect diagrams may be useful in this stage. and in further stages remind the users what aspects might be captured in the results - for those systems included - and those aspects which might not be captured - for those systems not included. After ranking or grouping the systems by their importance, consider the necessity, capability, and time required to model the less important systems. Finally down-select to the final set of systems to be included.

Having established the contributing systems, a diagram of high-level interaction of the major interactions among the systems should be created. In addition, the major aspects to be considered for each system, such as feasibility and viability, should be defined.

4. Definition of design space

For each system in consideration of design - in some cases multiple systems are considered for simultaneous design - the concepts which are to be evaluated, and the variables and ranges by which those concepts are defined should be established. The morphological matrix is a premier example of a tool for rigorously bringing all possible concepts to the table - without pre-established bias. The morphological matrix first asks the users to functionally decompose the system into its basic elements, and then establish all possible alternatives for each of those elements. The users can then consider any feasible combination of those alternatives. Although the number of concepts brought forward must be ultimately down-selected, the tool brings order to the establishment of concepts and can bring previously unconsidered options to the table.

Once the concepts have been established, each must be defined by a set of controllable design variables. Ranges can also be established for each design variable. If the problem is bounded by the modeling, this is not a necessary step, but it can also be useful to keep the

analysis within the likely regions of success, as well as help determine what system models are available - a model's predictive capability may only be established within certain variable ranges.

Check-point: At this point, the problem definition and bounding phase is complete. Further steps require a large investment in acquiring, learning, developing, and setting up models and an integrated modeling environment. Criteria established up to now should be re-examined for accuracy and completeness. If necessary, iterate among the initial steps.

5. Modeling tool selection

Investigate the modeling tools available for each system. Ask questions such as:

- Can this model represent the selected concepts and the established design ranges?
- Can this model predict system level metrics that are considered in the interaction of systems, and does it address the major aspects to be considered?
- Does this model have the predictive power needed for this problem?

Establish reasoning for the selection of modeling tools and then re-examine. Determine whether there are pieces missing when considering the establishment of a system of systems perspective. If so, what are they, and how can they be modeled?

Once the models have been selected, a baseline point should be established, and each model should be calibrated. Next, examine and verify each system model to determine if it can reasonably predict the system behavior away from the baseline point.

6. Develop integration framework

This step begins by establishing the detailed flow of metrics within and between system models. Information established and organized in steps 1 and 2 should be considered during this step to ensure the proper capture of desired effects. Using this detailed flow of information, create a blueprint of the modeling environment. Finally, determine what integration environment will be used, and implement the models following the blueprint.

7. Verification of baseline scenarios

Once the modeling environment has been developed and implemented, a baseline scenario should be established, including the baseline inputs for each model. Next, establish the baseline scenario - whereas each model is calibrated to a baseline system point, the baseline scenario refers to the concurrent condition of all systems. Because the system of systems is considerably more complex than the individual systems, verification is a difficult process, and acquiring the verification data for this purpose may be a significant task. For this reason, this should be considered in prior steps. There, one should ask about the necessity and degree of verification, and what type of verification data will be available, as this may affect modeling considerations.

8. Exploration and Decision Making

Once the behavior of the system of system model has been verified to an acceptable degree - likely through a consensus - the model is implemented for its established purpose - to explore and find solutions to the existing problem. The changes that to be modeled should be directly available from step 1, the problem definition, and will need to be translated into the modeling environment. These changes include the implementation of new concepts and technologies, the variation of design requirements or other design variables, the simulation of scenarios which represent future changes in uncontrollable aspects - including socioeconomic changes, policy laws, emission standards.

There are a wide variety of methods available for this step, including Pareto optimization, JPDM (Bandte et al., 1999), Top-Down Hierarchical Filtering (Ender, 2006), and metamodel representation and visualization. Prior to an implementation of a large scale exploration method implementation, it may be preferable to limit the design space to a small number of variables and gain an understanding of the expected behavior. In general, three types of exploration spaces are suggested:

- capability metrics vs. system variables - lead the design engineer towards system variables which maximize the capability metrics.

- capability metrics vs. capability metrics - bring forward important trades that need to be considered between capabilities.
- capability metric contours - using a select number of system variables, the plotting of capability metric contours can show how system variables interact.

Each of these exploration types will be demonstrated and discussed further utilizing the results of the proposed modeling framework.

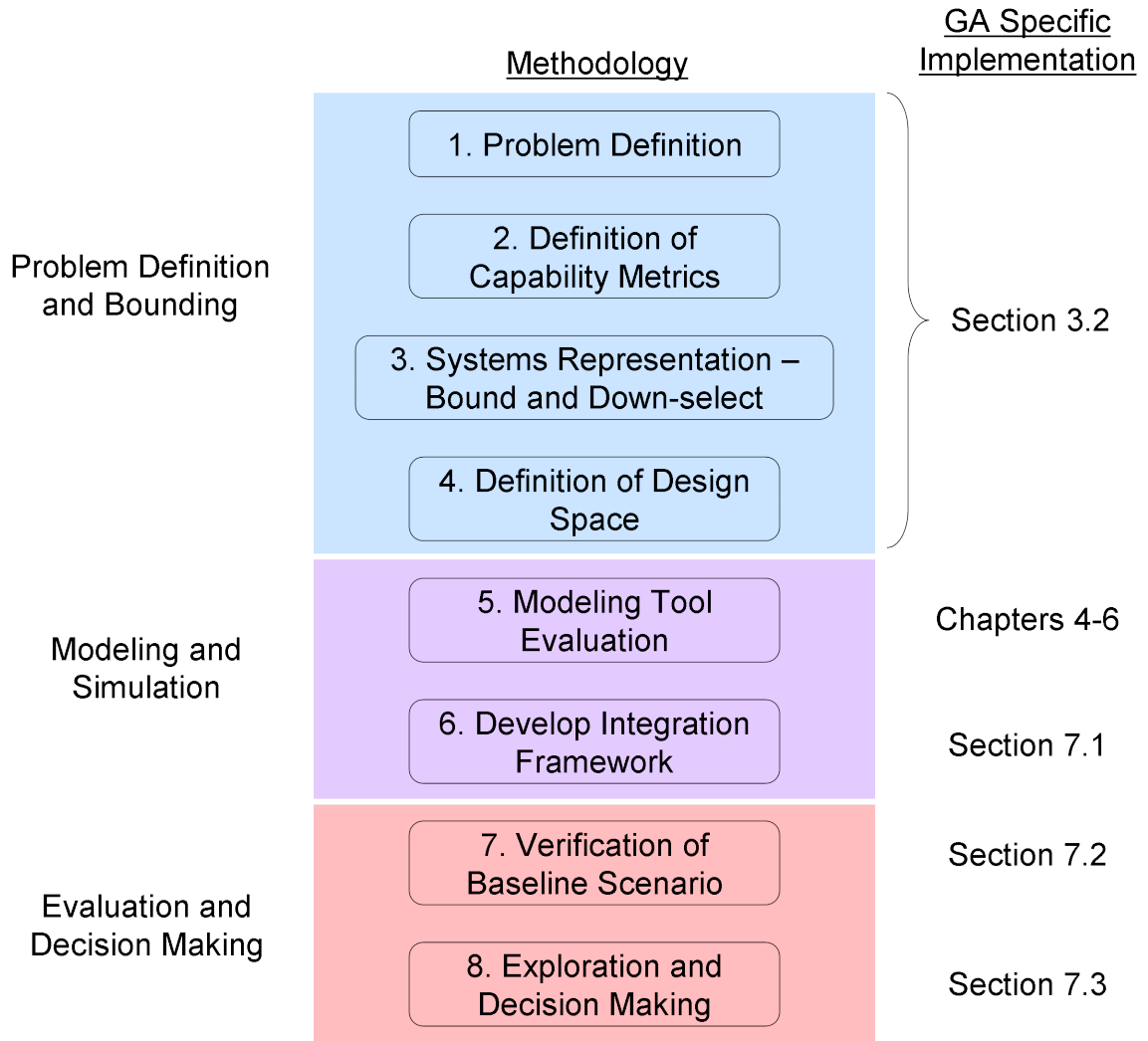


Figure 22: Methodology flow diagram, and locations of implementation.

3.2 Implementation: General Aviation Systems

As stated in Chapter 1, this thesis is concerned with addressing the design decisions associated with the implementation of future GA systems. For this purpose, the methodology described in the previous section is implemented for this problem - beginning here, and finalized throughout the remaining chapters of the thesis (refer to Figure 22).

1. Problem Definition

The quote at the beginning of Chapter 1 sets the tone and to a certain extent establishes the need - consider GA as a part of the future air mobility solution. Thus, the high-level definition of the problem is to seek GA system solutions which can contribute to the national mobility. While there are a number of aspects necessary for consideration, possibly the most important aspects that drive the successful implementation of a system or system of systems are the feasibility and viability aspects. Thus the problem will be guided by these aspects, and in an attempt to evaluate and select solutions that aim toward the goal of increasing mobility, the modeling should account for the most prominent of these effects.

In consideration of this problem, there are a number of markets to consider. The most notable markets existing today are the owner, taxi, and rental markets, each of which vary by the resources they choose to use, and the infrastructure under which they operate.

2. Definition of Capability Metrics


The idea of GA becoming a part of the solution to the future of air mobility might be measured differently by different entities. The consumer, for example might measure this by the price of the ticket or level of accessibility, or the manufacturer might measure this by the number of aircraft they sell, or the profits they achieve in doing so. From a holistic perspective though, mobility is probably best measured by the amount of demand for GA air travel that is captured, that is the maximization of air travel under conditions of feasibility and viability for all entities. This metric is termed viably captured demand. A thorough explanation of this metric definition and how it has been arrived can be found in Appendix B: Viably Captured Demand.

In addition to viably captured demand, a few other capability metrics need to be addressed. In an ideal world, all systems might collaborate to achieve a national objective of maximizing the viably captured demand. In the real world, systems act more independently and towards their own goals, and the system of systems which they compose is termed a voluntary system of systems (see Appendix B: System of Systems for more details). For example, a manufacturer may be likely to strive for a maximization of company profits, which does not necessarily coincide with the maximization of captured demand. Additionally, under the effects of competition, it is the free market system that drives this process.

A list of additional potential capability metrics are listed in Table 2, with those taken as the focus highlighted. Although some of these metrics could be considered as key to the success of a future GA system, for the purposes of demonstration, they are not necessary as they do not directly impact the aspects of system feasibility and viability.

Table 2: Capability Metrics List

<u>Capability Metrics</u>
Viably Captured Demand
Entity Profits
National Fuel Consumption
Average Accessibility
Airport Traffic
Environmental Noise
Job Production


 Thesis Focus

3. System Representation - Bound and Down-select

Having defined the capability metrics - most importantly the viably captured demand and the entity profits - the systems must be selected which can sufficiently capture the effects from design changes in the systems of interest. Table 3 displays a short list of systems that might be considered to interact with the GA systems, directly or indirectly.

Table 3: GA Systems List

GA Systems
Traveler Demand
Aircraft Manufacturer
Service Provider
Navigational Infrastructure
Traffic Control
Airports
Policy Planning
Weather
...

 Thesis Focus

For this thesis it is desired to demonstrate the system of systems, capability-based design environment, and thus in the following, it is hypothesized what systems need to be addressed, and what key feasibility and viability aspects of these systems should be addressed.

Modeling Research Question: What systems need to be addressed to demonstrate design for capability and what are the key feasibility and viability aspects of these systems?

Modeling Hypothesis: The aircraft manufacturer, service provider, and travel demand systems comprise the systems representation required to achieve a design for capability demonstration. The key feasibility and viability attributes are summarized in Table 4.

Table 4: GA Down-selected systems representation

Aircraft Manufacturer	Aircraft feasibility – physical capability to complete a specified mission Production viability – economic capability to supply specified aircraft
Service Provider	Scheduling feasibility – physical availability of aircraft with respect to demand Operational viability – economic capability to service specified demand
Traveler Demand	Modal feasibility – Travel mode is locally accessible for service from origin to destination Viability – Selection of travel mode and decision of ownership makes “pocketbook” sense

In addition, a more detailed summary of each system, with relation to their key modeling aspects are given below. Figure 23 additionally postulates the primary interactions among

and within these systems. These descriptions will aide in further problem definition and bounding procedures.

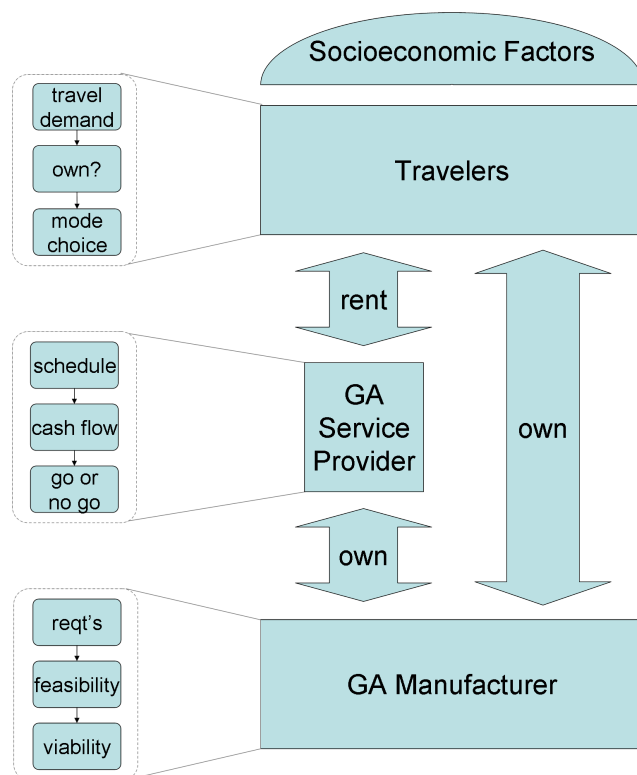


Figure 23: Interactions of the down-selected systems representation.

Aircraft Manufacturer: The manufacturer seeks production of an aircraft that satisfies the needs of the customers - the individual consumers and the intermediate service providers. Their solutions are bound by physics, manufacturing capabilities, and the economics of production. Modeling of this entity will focus on translating performance requirements into a feasible aircraft design, and further estimate the cost of the aircraft to the consumers, constrained by the manufacturer's viability.

Travel Demand: Consumers fulfill their needs and desires to travel after careful consideration of the travel modes available to them. Modeling of these consumers focuses on determining if and how often they would choose GA as a mode of travel, and if ownership of GA aircraft is beneficial.

Service Provider: The service provider seeks to provide transportation services to consumers, given that they can logistically schedule the demand within a viable mode of operation. Modeling of this entity will focus on determining the proportion of demand that can be scheduled - which includes understanding how demand is distributed spatially and temporally - and a means to analyze and improve their chance of viability.

4. Definition of Design Space

In this thesis, two primary aircraft types are studied, the single engine piston - referred to as the general aviation piston (GAP) - and the light twin engine jet - or general aviation jet (GAJ). These aircraft types have been chosen for several reasons. First, they are the most actively produced and utilized aircraft in the GA system. Secondly, they embody the two most emphasized aircraft types of future GA research - the Personal Air Vehicle, or PAV, and the Very Light Jet, or VLJ. Table 5 displays a morphological matrix for the selected attributes of each of these systems. Notice that the unselected options constitute a large number of concepts if the combinatorial of all alternatives is considered - all possible concepts for future evaluation.

Table 5: Aircraft system concept morphological matrix.

Sub-system				
Propulsion Type	Piston – prop	Piston – Fan	Turboprop	Turbofan
Number of Engines	1	2	3	4
Wing Configuration	Conventional	Canard	Other	
Wing Placement	High	Low		
Technologies	SFC	Weight Reduction	Drag Reduction	Avionics (Easy-to-Fly)

GAP Selection
 GAJ Selection

The possible list of aircraft system variables could be grouped into the design mission requirements and the design definition variables. The latter group defines variables such as

the wing loading, propeller activity factor, and the wing aspect ratio. The design mission requirements group determine the relative size of the aircraft, and directly affect the desirability to the customer - balanced by the cost of meeting the requirements. It is assumed that for a given set of mission requirements, the primary design definition variables can be optimized - by minimizing gross weight - such that requirements effects are of significantly greater immediate importance. This was seen to be the case in the work by Ahn et al. (2002), as exemplified in Figure 10. The specific mission design requirements addressed in this model include design speed, payload, and range. The value ranges of these variables will be adjusted as necessary for the purposes of displaying results.

The service provider is also studied as a designable system in this thesis, thus a similar design space definition must be performed. For the GAP, which represents the PAV idea, the service provider has been envisioned as a local rental or taxi type service, much like a car rental agency. The GAJ on the other hand operates more similarly to a specialized regional airline, although with smaller planes offering on demand service. The morphological matrix representing other possible alternatives is displayed in Table 6, with the selected operational attributes highlighted.

Table 6: Service provider system concept morphological matrix.

Operational Attribute				
Scheduling	Scheduled	On Demand	OTHER	
Networking	Distributed Network	Central Network	Local	
Trip Type	Roundtrip	One-Way	Both	
Billing	Charter	Per Seat	Per Time	Per Mile

GAP Selection
 GAJ Selection

The design variables associated with the service provider will be discussed in more detail later, but can be simply described as the size of the aircraft fleet, and the mark up put on the price of the ticket.

5. Modeling Tool Evaluation

At this step, modeling tools are examined for each of the three represented systems, and down-selected to a set which will contribute to the final model. Additionally, gaps in these tools are identified, and a number of technical challenges are posed in the form of modeling research questions, and then formally answered in the modeling hypotheses. Each of the models and the sub-models under consideration are described briefly in this section. Full detail is given in Chapters 4-6 for the aircraft manufacturer, travel demand, and service provider models respectively. Additionally details of specific sub-models are indicated in the proceeding descriptions. Displayed in Table 7 is the matrix of system modeling alternatives considered in this thesis.

Table 7: System modeling alternatives.

System				
Aircraft	GASP	FLOPS	OTHER	
GA Travel Demand	TSAM	<i>Mi</i>		
Service Provider	MCATS	ALCCA	OTHER – Network	OTHER – Local

GAP Selection
 GAJ Selection

Beginning with the aircraft and manufacturer representation, there exist a number of physics and empirical-based legacy codes which address this system. The General Aviation Synthesis Program (GASP) was developed by NASA to study GA aircraft performance and cost, and uses a combination of statistical regressions and physics-based routines. The code, developed in the 1970's has not seen widespread use, and although some updates have occurred, it has been questioned as applicable to GAP size aircraft (Snyder et al., 1977).

In addition to these concerns, for the purpose of demonstration, the primary necessity of the aircraft representation is that there is a transparency between the changes in the system variables - namely the design requirements - and the aircraft system metrics - namely the costs. Legacy codes tend to require a substantial effort in aircraft definition - especially

when a similar model is not available through prior research - and when there unexpected phenomena occur in the metric trends, it is not always immediately apparent what mechanism is the cause. This can make accurate, parametric representation of the existing GA fleet a cumbersome process. For this reason, an alternative solution is pursued - one which melds physics-based analysis with up-to-date weight and cost models- leading to the first modeling research question:

Modeling Research Question 1.1: How can the existing GA fleet be represented in the aircraft system modeling?

Modeling Hypothesis 1.1: The current fleet can be surveyed and databased by weight and cost, and regressions can be created which work in concert with a physics-based performance and sizing routine.

For the GAP, the physics-based performance and sizing routine will consist of a “home-grown” coding, utilizing the fundamental equations of aircraft design. For the GAJ, a FLOPS model has been acquired and modified to represent VLJ size aircraft. Each of the respective routines has been connected with regressions of sizing parameters - component weight fractions and fuselage scaling - and costing routines and shown to represent the existing fleet well. The final models are described in Sections 4.1 and 4.2 for the GAP and GAJ respectively.

Next, the model which will represent the demand for GA travel is selected. As discussed earlier, TSAM and Mi are the two most prominent codes which attempt large scale simulation of the NTS in order to predict the magnitude and relative travel marketshare of GA. From a high-level perspective, these codes were developed for similar purposes- to study GA travel - and thus they share a number of attributes, as seen in the comparison table, Table 8.

The difference between the codes lies in the focus of their purpose. TSAM was developed to assess the impacts of the SATS program on the NTS, which puts focus on the operational aspects of the GA system. For this purpose, TSAM has high spatial granularity, and in addition predicts the travel routes of GA aircraft which in turn can help measure the impact

Table 8: Comparison of Mi and TSAM modeling attributes.

Attribute	TSAM	Mi
Travel Time	Door-to-door	Door-to-door
GA Performance	Independent input	Independent input
GA Cost	Independent input	Independent input
Spatial Granularity	County Level	Abstract Locales
Time Granularity	Annual	Annual
Travel Mode Distribution	Aggregate county level distribution	Consumer level decision model

to air traffic. As a trade, the predictive power of GA demand growth in TSAM was not the central modeling issue. Thus TSAM prescribes the distribution of demand to the various travel modes - car, commercial airline, and GA - from the county level, as depicted on the left of Figure 24.

On the other hand, Mi was developed with a greater focus on the capability to predict GA demand growth in relation to system level attributes. As depicted on the right side of Figure 24, the modal distribution is an aggregate of the agent decision making process over a large number of agents and a large number of trips. This process enhances the capability to capture the individualistic nature of travelers, and furthermore better capture the effects of changes to the vehicles. For these reasons Mi is chosen as the primary GA travel demand model.

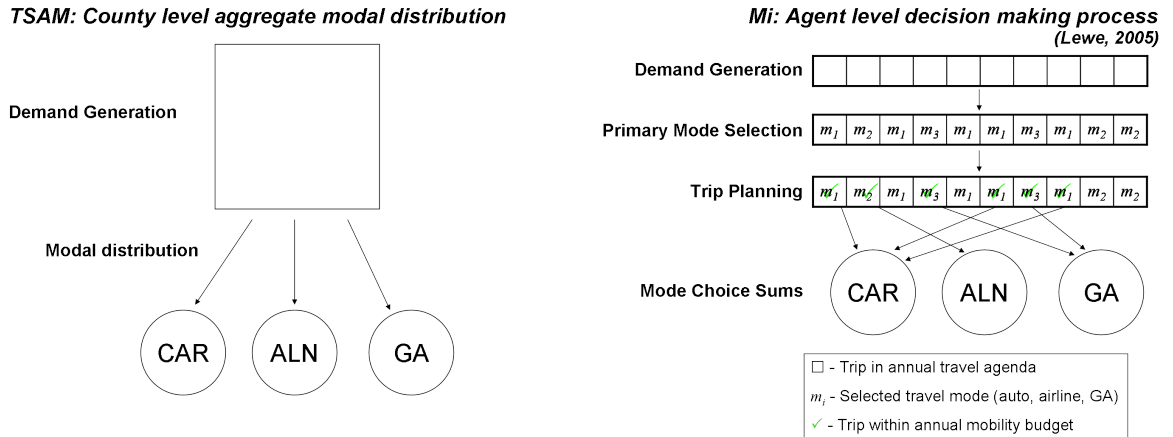


Figure 24: Comparison of Mi and TSAM modal demand distribution.

There are a few modeling aspects which *Mi* does not account for but which are seen as necessary to capture the interactions as desired in Figure 23. These include the ability to predict vehicle ownership - both *Mi* and TSAM focus on the demand for travel, not travel resources - and the distribution of demand, both spatially and temporally. These concerns have been laid out in a number of modeling research questions.

Modeling Research Question 1.2: How can the prediction of aircraft ownership be implemented into the existing demand model?

Modeling Hypothesis 1.2: An agent level model which accounts for the long term utility benefits - that is the relative time and cost savings as compared to other modes - and compares them to the costs of ownership can be used to predict aircraft ownership.

As it stands, the size of the owner population in *Mi* is predetermined by imposed probability of an agent given the owner status. This does not allow the effects of the aircraft's cost attributes, particularly the acquisition cost, to be propagated to the consumer. *Mi* accounts for cost through a price index, representing a rental rate. Owning and renting agents can use this independent input to determine if GA is proper for a given trip, but not to determine their ownership status. It is posed here that an ownership model, which accounts for the consideration of the aircraft related costs against the long term utility of owning the aircraft, can be implemented to account for the effects of aircraft design changes on ownership population. The implemented ownership models are discussed in Section 5.2.

Modeling Research Question 1.3: How can the set of service provider locations be defined to fairly represent the nature of GA?

Modeling Hypothesis 1.3: A clustering algorithm can group county populations into a population that shares a common service provider.

Modeling Research Question 1.4: How can demand be spatially distributed to the service provider locations?

Modeling Hypothesis 1.4: Demand can be distributed spatially based upon the socioeconomic factors - population, income, sales - defining each population.

Modeling Research Question 1.5: How can demand be temporally distributed at the service provider locations?

Modeling Hypothesis 1.5: Historical travel data can be used to model when air travel tends to occur - across the year and throughout each week.

This modification to Mi is linked to its method of representing the NTS - as an abstract entity. This means that the resultant demand is not explicitly distributed spatially or temporally, rather by a small set of locale abstraction - large, medium, small, and non-metro. GA usage has the advantage of having at its disposal a large number of spatially distributed runways, and thus it is envisioned that future service providers would operate locally, much like a car rental agency, rather than as a centralized operation. To fairly analyze these service providers, it is necessary to implement methods to spatially distribute the demand to real locations within the US, as the feasibility and viability of the service provider will be dependent upon the local magnitude of demand. Temporal distribution is also important, as rushes and lulls in demand can decrease the efficiency of aircraft scheduling. Details of these models are discussed in Section 5.3.

The final modification seen as necessary is the expansion of detail in the calibration of the Mi model. The model was calibrated to the 1995 American Travel Survey (ATS), which contains specific information concerning the travelers - allowing the agent representation - but unfortunately does not well specify GA into separate markets.

Modeling Research Question 1.6: How can demand markets be further differentiated within Mi ?

Modeling Hypothesis 1.6: The annual General Aviation and Air Taxi Activity (GAATA) survey can be used to estimate the differentiation of demand markets within the original 1995 ATS data.

The annual GAATA survey tracks GA usage by the number of hours performed with a number of demand markets - including differentiation by ownership, rental, and air taxi.

Unfortunately, GAATA does not track the individual characteristics of the travelers - their socioeconomic characteristics or their annual travel attributes. This means that it cannot replace the ATS in calibrating the M_i model, but as stated in the hypothesis above, the market differentiation in the GAATA survey might be applied within M_i in lack of complete survey data. The implementation of the GAATA survey characteristics and calibration results are discussed in Section C.2.

Finally, the service provider modeling is considered. The GAP and GAJ operations will be fundamentally different in nature. The GAJ operation is considered on demand, point to point, but still operates on a per seat basis. This means that the operation will be something of a very specialized regional aircraft, with a great amount of freedom in adjusting its routing. The Aircraft Life Cycle Cost Analysis, or ALCCA, program addresses the costs associated with operating a fleet of aircraft within a commercial airline setting (Mavris and Galloway, 2001). In lieu of acquiring and implementing a large scale operation analysis, ALCCA is chosen to represent the scheduling and economics of the GAJ service provider.

The GAP service provider on the other hand acts on the local level and this type of analysis has not been well documented. To model such an operation, one needs to capture the business cost aspects, but in this case it is most important to parametrically capture the effects of aircraft related costs. Thus these costs are investigated and models are created around the findings. Additionally, a scheduling algorithm, which utilizes the outcomes of the temporal distribution of demand discussed earlier is developed and implemented. These models are discussed in detail in Section 6.1.2.

Steps 6-8: Integration Framework, Verification, and Exploration

The display of these steps will be continued after a detailed description of each of the system models in the following three chapters. Step 6 is presented in Section 7.1, step 7 is presented in Section 7.2, and step 8 is presented in Section 7.3.

Chapter IV

AIRCRAFT MANUFACTURER MODELING

The aircraft is the primary resource in the GA transportation system. The goal of modeling is to represent the aircraft performance capabilities according to the physics and manufacturing processes to which it is bound, as well as the price at which it can be viably offered to the customer. The consumer and service provider models can then use this information to gauge the demand for the aircraft - its usage and the product itself - as well as the viability of meeting that demand.

Within this dissertation, the GA fleet is divided into two categories; the general aviation piston (GAP) and the general aviation jet (GAJ). The GAP category represents single engine piston (SEP) aircraft, while GAJ is most representative of the light, twin engine jets. The General Aviation Manufacturers Association (GAMA) statistics¹ show that these types are most utilized for travel, and the SEP have a significantly greater volume of aircraft and utilization hours among all categories.

4.1 The General Aviation Piston

Although the SEP is considered the “typical general aviation aircraft” (Turnbull, 1999), design, sizing, and costing of SEP aircraft is not as well documented as other types of aircraft. Monolithic codes including the Flight Optimization System (FLOPS) and the General Aviation Synthesis Program (GASP) have been used to analyze SEP designs, but the applicability and accessibility of these programs is a hindrance to their use. FLOPS is readily available, but this code has been developed for commercial transports and military jets, and not well tested for SEP type aircraft (McCullers, 2001). GASP, developed by

¹GAMA annually publishes the General Aviation Shipment Report (GAMA, 2006a), and the General Aviation Statistical Databook (GAMA, 2006b), which include statistics from their own surveys and records, as well as prominent results from the FAA’s General Aviation and Air Taxi Activity Surveys (GAATA) (FAA, n.d.).

NASA in 1978, may be a feasible alternative (Hague, 1978), but has been argued to be applicable only to larger GA aircraft (Snyder et al., 1977). The DARcorporation has also designed a preliminary sizing routine specifically for GA aircraft, with a level of detail more suitable for stages beyond conceptual design (Anemaat et al., 1997; Locke and Anemaat, 1997; Roskam and Anemaat, 1996).

While these codes could be implemented in the future, a parametric model that provides a transparent, physics based representation of modern SEP aircraft is desired for the purposes of a proof-of-concept demonstration. Thus, a sizing and costing algorithm is developed here for SEP type aircraft. This will allow the use of up-to-date weight and cost regressions based on the most recent data, and will be heavily weighted towards sizing of aircraft, with the synthesis represented by standard disciplinary metrics.

As with most aircraft sizing problems, major uncertainties arise in estimating the structural and propulsive weights, as there are no generalized, physics based analytical forms. Empirical relations are needed to realize a parametric design and sizing environment. While several sources of parametric weight estimation relations exist, they are often application specific, or span too broad. Figure 25 shows the empty weight fraction of the most popular SEP aircraft against the aircraft's takeoff gross weight, with comparison to the estimate given by Raymer (1999).

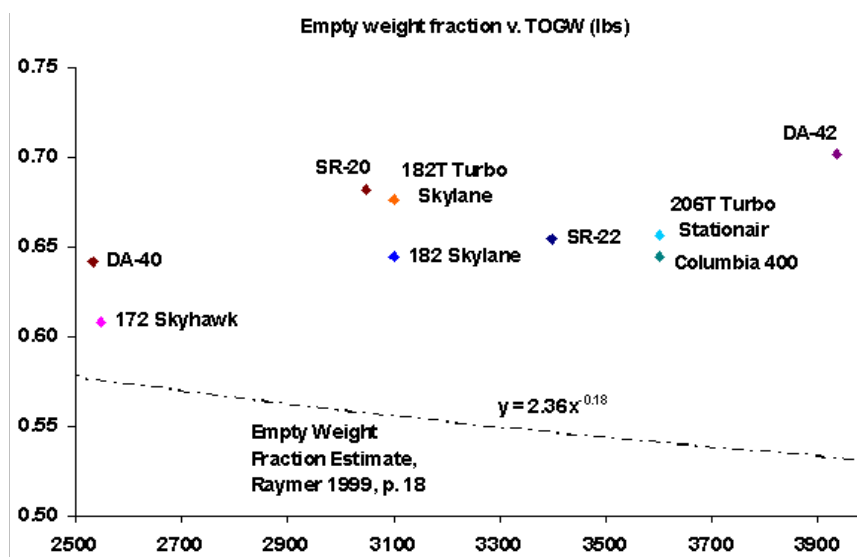


Figure 25: Modern SEP aircraft weight data.

After seeing the difference in characteristics of modern, popular SEP aircraft to empirical weight regressions used by past authors, it was decided to build a simple aircraft sizing and costing model that is effective at representing today's SEP fleet. In this section, a set of simple, up-to-date weight and cost estimation relations will be presented for use in the aircraft sizing algorithm.

4.1.1 Weight Estimation

Physics based estimation of aircraft weights have always been elusive, and thus analysis relies on empirical models, representative of historical trends. There are a handful of equation sets and programs that exist, some readily accessible and some not. Raymer (1999) and Ibrahim and Mohnot (2006) both provide weight estimation relations, specifically for GA aircraft. These regressions attempt to cover a wide range of aircraft types, diminishing the accuracy within a specific band of aircraft.

To build a model, a representative group of existing aircraft is sought as a regression database. The FAA registry shows thousands of aircraft models in the GA fleet today, but it is not feasible to include all of these aircraft (FAA, 2007*b*). The most relevant aircraft are those that are in greatest demand today. This leads to selection of the top 10 shipped piston aircraft, as reported by the GAMA (2006*a*), to make up the regression database. This group of aircraft represent nearly 80% of all shipments, as seen in Figure 26.

This group includes a fair mix of the time proven designs, and the up-and-coming designs. Not surprisingly, all are SEP, except for the Diamond DA-42, which is a twin engine piston. Because the focus here is on SEP aircraft, the DA-20, a two seat SEP, is used in place of the DA-42, and also adds two seat representation to the database. The SEP regression database used here is shown in Table 9.

Given the level of information readily available, the aircraft empty weight is broken into two primary components: the airframe weight and the engine weight. The airframe weight is defined here as the empty weight minus the engine weight.

Airframe

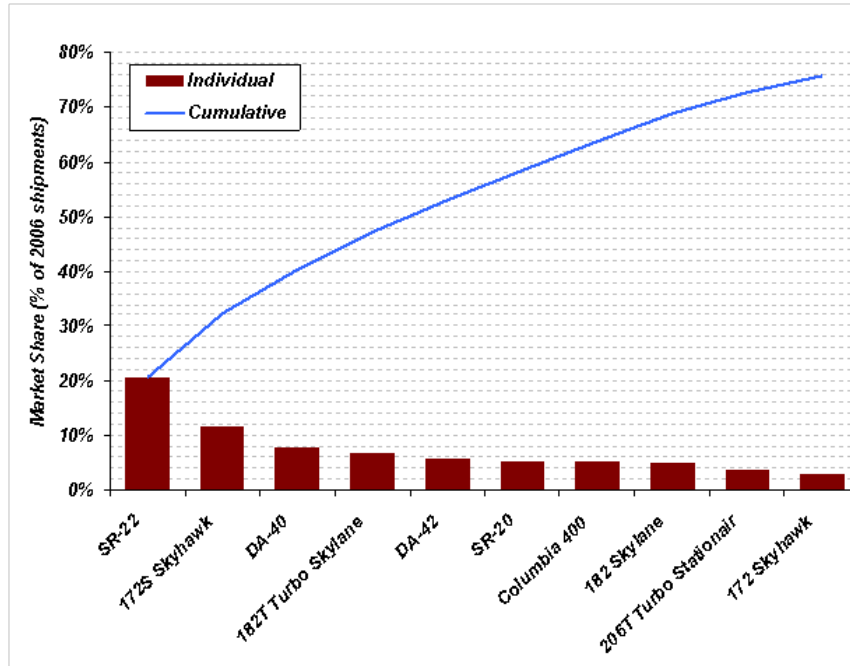


Figure 26: Top shipped aircraft in 2006.

Table 9: Aircraft database: weight and performance summary.

	TOGW max (lbs)	Empty Weight (lbs)	Airframe Weight (lbs)	Vmax (kts)	Engine Weight (lbs)	SHP	Engine Model
SR-22	3400	2225	1785	185	440	310	IO-550-N
172 Skyhawk	2550	1550	1282	127	268	160	IO-360-L2A
DA-40	2535	1627	1362	144	265	180	O-360-A4D
182T Turbo Skylane	3100	2097	1623	176	474	235	TIO-540-AK1A
DA-42	3935	2761	2170	182	591	270	2X TAE Centurion 2.0
SR-20	3050	2080	1780	165	300	200	IO-360-ES
Columbia 400	3600	2500	1942	235	558	350	TSIO-550-C
182 Skylane	3100	1997	1558	150	439	230	IO-540-AB1A5
206T Turbo Stationair	3600	2362	1862	178	500	310	TIO-540-AJ1A
DA-20	1764	1164	911	145	253	125	IO-240-B3B

The airframe weight is influenced by the physics of flight and by the manufacturing methods and technologies utilized during production. Correlating weights to the manufacturing methods is not a straight-forward task, and is not attempted here. The airframe weight is influenced primarily by the forces acting on it during flight and landing. The total weight of the aircraft influences the vertical forces on the aircraft, and is fixed for a given weight, while the drag force increases with speed for a given configuration. These forces typically need to be accounted for under various speed and loading combinations, both static and dynamically. Unfortunately, these analyses are outside the scope of this research, and rather correlation of speed and takeoff gross weight to the airframe weight fraction is pursued. Figure 27 shows a plot of airframe weight fractions against the takeoff gross weight for the SEP database.

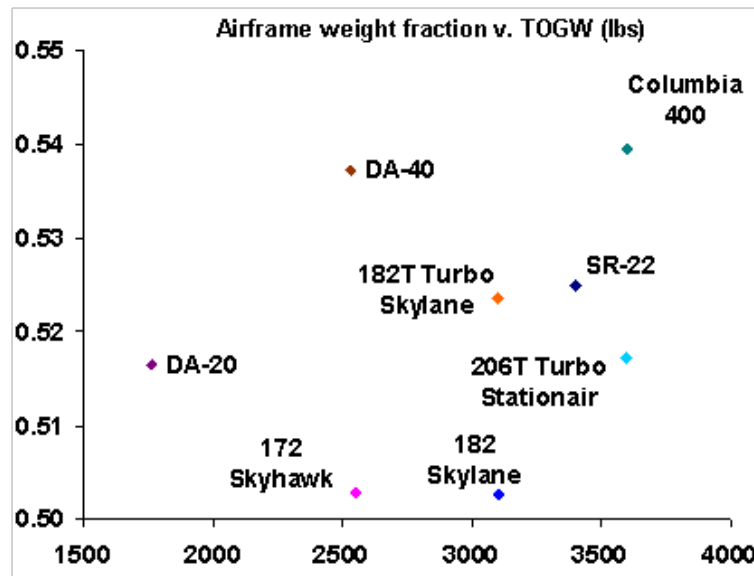


Figure 27: Airframe empty weight fractions of SEP database.

The total variation on airframe weight fraction is confined to between 0.50 and 0.54, and in general the airframe weight fraction tends to increase with takeoff gross weight, but the trend is not well defined. The takeoff gross weight is also strongly influenced by the aircraft speed, due to increasing structural weight, engine weight, and fuel consumption, and it is difficult to separate the two effects. But, a plot of the airframe weight fraction against the maximum cruise speed, as seen in Figure 28, shows a more defined trend. This trend has

been converted to a piecewise formulation for estimating the GAP airframe weight fraction, given by equations 1 and 2.

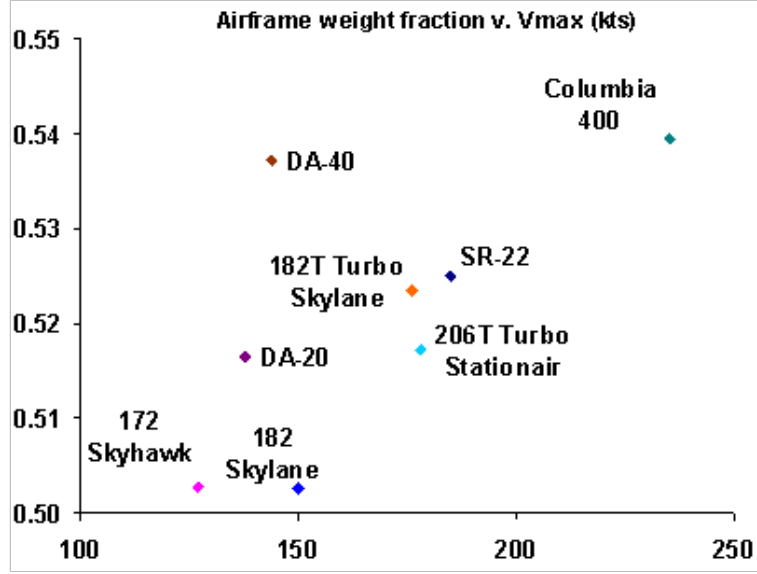


Figure 28: Airframe empty weight fractions of SEP database.

Maximum cruise ≤ 150 kts:

$$\frac{W_{af}}{W_g} = 0.5026 \quad (1)$$

Maximum cruise > 150 kts:

$$\frac{W_{af}}{W_g} = 0.5026 + \frac{0.0369}{85}(V_{max} - 150) \quad (2)$$

Engine

The majority of production piston powered GA aircraft use one of two engine manufacturers: Lycoming and Teledyne Continental. These companies offer multiple variations of several sizes in four, six, and eight cylinders for engines of this application type. When each engine enters service, a type certification datasheet becomes available which includes weight and horsepower ratings, as well as the type of fuel injection and air intake (FAA, 2007d). This information was collected for 15 engine types, including their variants. The set spans shaft horsepower from 115 to 350 SHP.

Graphical representation of the engine database, see Figure 29, shows that the weight of the engine can be estimated based on the SHP rating and the type of air mixture - normally aspirated (normal) or turbocharged (turbo). A number of vertical stripes can be seen in the plot, likely due to post-design structural requirements, causing a variant to be formed. The only group that fall is off the regression line is the lowest SHP rating group, around 115 HP. The rotax 912 is included to correct the misleading leveling off the Lycoming engines at low SHP ratings. This apparent leveling is likely caused by engine variants which are deratings of larger engines or because designing an engine with fewer cylinders was not cost effective (Lycoming does not produce engines under four cylinders).

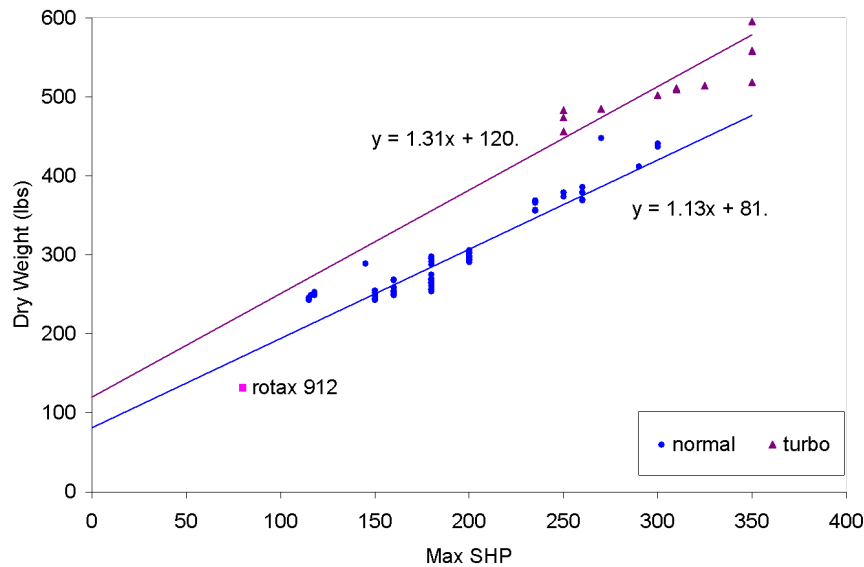


Figure 29: Engine database: Weight v. SHP, with regression lines.

Several regressions were attempted, with a linear regression producing the best and most logical fit. The power of a reciprocating engine is proportional to the volume of its cylinders, which is in turn proportional to the volume of the engine, and thus the weight of the engine. Equations 3 and 4 are used to determine the engine weight in the analysis environment. The performance effects of turbocharging are also included in the sizing routine, by removing the engine power lapse rate to air density - typically true up to 12,000 ft.

Normally Aspirated (lbs):

$$W_{eng} = 1.13 \cdot SHP + 81 \quad (3)$$

Turbocharged (lbs):

$$W_{eng} = 1.31 \cdot SHP + 120 \quad (4)$$

4.1.2 Performance and Sizing

The performance and sizing theory used in this analysis can be found in the standard texts on aircraft performance and conceptual design and sizing, and adhere to the basic theories of aerodynamics, propulsion, and physics (Torenbeek, 1982; Johnson, 1994; Anderson, 2000). The analysis focuses on the sizing of aircraft - wing area, engine power, engine weight, fuel weight, airframe weight - with respect to the mission requirements. The specifics of the design geometry and engine cycles impact the design, but are sufficient to be represented by their disciplinary metrics; they are of greater importance after requirements are settled upon or under the impacts of revolutionary technologies.

Aerodynamics

The aerodynamics routine first sizes the wing according to the required stall speed at takeoff gross weight, typically the most stringent FAA requirement for GA aircraft. This provides the constrained optimal wing area, unless the mission requirements are undemanding, at which point a lower stall speed will result in optimum performance. The wing area is calculated according to:

$$S = \frac{W_g}{\frac{1}{2}\rho_{sl}V^2C_{L,max}} \quad (5)$$

At cruise, the lift coefficient is calculated at mid-cruise weight in the standard manner, and the total drag coefficient of the aircraft is then found as follows:

$$C_D = C_{D,f} + C_{D,o} + \frac{C_L^2}{\pi eAR} \quad (6)$$

The total drag is then passed to the propulsion routine, and the lift to drag ratio is passed to the sizing routine.

Propulsion

The propulsion system is sized for the beginning of cruise at a specified throttle setting. Given the air density, speed, and aerodynamic drag, the ideal induced and the profile power required are calculated as follows:

$$P_i = T \left(\frac{V}{2} + \sqrt{\left(\frac{V}{2}\right)^2 + \frac{T}{2\rho A}} \right) \quad (7)$$

$$P_o = \frac{N}{8} \rho \varpi^3 c_{do} r^2 c \quad (8)$$

The total shaft power required at the engine is found by accounting for losses due to non-ideal blade loading, and any shaft or gearbox losses:

$$P_T = \frac{1}{\eta_{gb}} (\kappa P_i + P_o) \quad (9)$$

Finally, the sea level static power rating of the engine is determined by accounting for the density increase from cruise altitude to sea level and setting the throttle to full. If turbocharging is implemented, power is assumed not to change with altitude² and the density term is omitted.

Normally aspirated:

$$SHP = P_T \frac{1}{f} \frac{\rho_{sl}}{\rho} \quad (10)$$

Turbocharged:

$$SHP = P_T \frac{1}{f} \quad (11)$$

From above, the total shaft power required at cruise is known, as well as the useful aerodynamic power produced. The propeller efficiency is the ratio of the useful power to the required power:

$$\eta = \frac{TV}{P_T} \quad (12)$$

²This holds true for most typical SEP cruise altitudes (< 12,000 ft).

Without a proper piston engine cycle analysis, the specific fuel consumption must be given, although some simple accounting for variation in throttle setting is applied. Given the consumption at 75% and 100% throttle, the consumption at any other setting is linearly interpolated. Trends found in Highley (2004), a report on the modeling of piston engine cycles, were implemented for this purpose.

Sizing

The sizing routine has at its core the Breguet range equation, for which the disciplines are represented as lift to drag ratio, propeller efficiency, engine specific fuel consumption, and component weight fractions. Because SEP type aircraft have small fuel fractions, the effects to performance across the mission are considered negligible. The closed form of the Breguet range equation is used, with performance calculated at mid-cruise weight. The standard Breguet form is manipulated to solve for the mission gross weight, as in Equation 13 ($[W] = lbs; [R] = ft, [bsfc] = lbs/HP/s$).

$$W_g = \frac{W_{pl}}{\exp(-\frac{bsfc \cdot R}{\eta \cdot 550 \cdot \frac{L}{D}}) - \frac{W_{af}}{W_g} - \frac{W_{eng}}{W_g}} \quad (13)$$

Payload and range are explicitly represented in this equation, and speed is accounted for through the aerodynamic and propulsion routines. The cruise range includes an implied equivalent cruise distance to account for the takeoff, climb, alternate airport, and landing segments. The disciplinary metrics, including the empty weight and engine weight fractions are calculated as described in the preceding sections. Because all disciplinary metrics rely on the takeoff gross weight, the solution requires an iteration process.

4.1.3 Cost Estimation

A dependable and realistic cost model is essential to the integrated analysis environment. Without the reliance of the cost module, the propagation to owner and service provider ownership and operation models cannot be taken seriously. Thus a strong effort is made to have an accurate representation of the cost trends of today's aircraft. All costs in this section are displayed in 2007USD unless otherwise noted. Additionally, this section only addresses costs of acquisition. Operating costs are also associated with the aircraft, but

they are addressed under the service provider analysis, which includes all aspects - aircraft related or otherwise.

The complex and proprietary nature of the aerospace industry makes accurate cost estimation a difficult problem. Although a few cost estimating programs exist, there are none explicitly designed for up-to-date GA aircraft. The Aircraft Life Cycle Cost Analysis (ALCCA) code, documented by Mavris and Galloway (2001), is a weight based component build-up program. This program has been popular in the cost estimation of commercial transport aircraft and their operations, but has not been shown to work for GAP type aircraft. Implementation by the author showed that results were questionable, and retooling the program for GAP types would be cumbersome. Thus a model is pursued that captures the parametric effects of the GAP's physical attributes on its cost.

In this study, cost estimation is based on statistical fitting of historical data, primarily the published purchase cost of aircraft and their components in 2007. These are *costs to the consumer*, rather than *cost of production*, where the difference between the two will consist of marketing costs, profits, and retail mark ups. These statistics are not well known, and thus it is the aircraft cost to the consumer, or retail price, that is estimated. This implies that the price provides sufficient margin for viability, without explicitly assessing the economics of the manufacturer.

The aircraft is divided into three major components: airframe, engine, and avionics. These divisions are made to allow enhanced parametricity in the design process, so later one can switch engines among airframes or apply cost reductions to the components rather than the entire aircraft. There is no model for avionics cost, only a classification by standard (~\$12,000) and premium (~\$25,000) configurations. These costs are isolated from the costs of the other components. Premium avionics usually include an autopilot system and weather related navigation equipment in addition to the standard equipment.

Engine Acquisition

Engine prices found in Lycoming (2007) are cross-listed with the horsepower and weight data collected from the type certification datasheets, as described in the weight estimation section, resulting in approximately 200 data points. Plotting the engine price against the

engine weight, see Figure 30, a regression seems to provide a reasonable estimation.

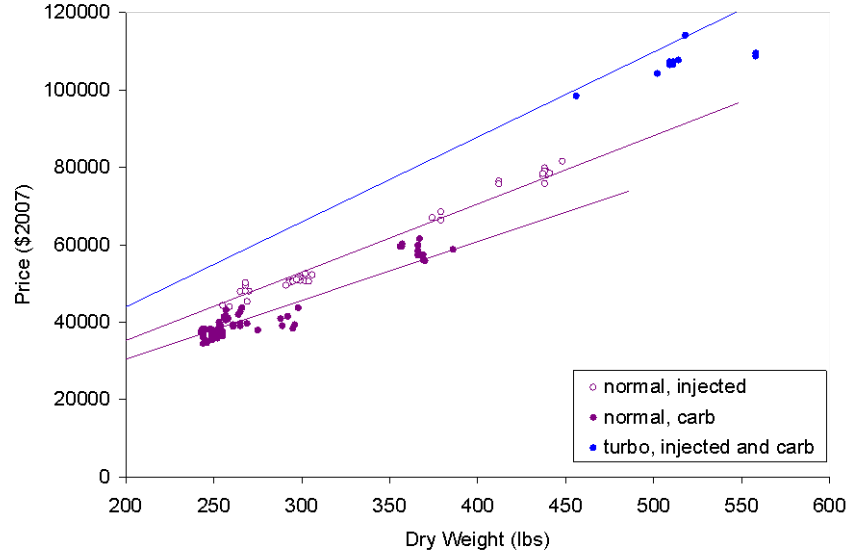


Figure 30: Engine database: Cost v. Weight, with regression lines.

A cost per pound model is chosen for regression. The normal, injected engines, which have the greatest weight span exemplify the validity of choosing this model. By this metric, GA piston engines cost between \$140 and \$220 per pound. The regression models are displayed below ($[W] = lbs; [C] = \$2007$).

Carbureted, normally aspirated:

$$C_{eng} = 139.88 \cdot W_{eng} \quad (14)$$

Fuel injected, normally aspirated:

$$C_{eng} = 162.54 \cdot W_{eng} \quad (15)$$

Carbureted or fuel injected, turbocharged:

$$C_{eng} = 217.76 \cdot W_{eng} \quad (16)$$

Airframe Acquisition

Prices of the database aircraft were gathered from the manufacturer’s published information, in the “standard” configuration (Cessna, 2008; Cirrus, 2008; Diamond, 2008; Columbia, 2008). The airframe cost is assumed to be the total aircraft cost less the cost of the engine and avionics. Recall that these are costs to the consumer, and while this division of costs is not intuitive - consumers will buy the entire aircraft - the end result will be a model that parametrically estimates the cost to the consumer based upon the aircraft’s physical attributes. Costs for the database aircraft are summarized in the table below.

Table 10: Aircraft database: costs summary.

	Total Standard	Engine	Avionics	Airframe	Quantity Shipped (2002-2006)
SR-22	\$ 371,200	\$ 80,000	\$ 25,000	\$ 266,200	2146
172 Skyhawk	\$ 219,500	\$ 49,228	\$ 12,000	\$ 158,273	1660
DA-40	\$ 245,570	\$ 40,636	\$ 12,000	\$ 192,934	868
182T Turbo Skylane	\$ 379,500	\$ 123,000	\$ 25,000	\$ 231,500	564
DA-42	\$ 532,675	\$ 108,306	\$ 25,000	\$ 399,369	231
SR-20	\$ 276,690	\$ 52,500	\$ 25,000	\$ 199,190	574
Columbia 400	\$ 485,900	\$ 112,500	\$ 25,000	\$ 348,400	285
182 Skylane	\$ 349,500	\$ 81,008	\$ 25,000	\$ 243,493	804
206T Turbo Stationair	\$ 514,000	\$ 145,000	\$ 25,000	\$ 344,000	350
DA-20	\$ 169,389	\$ 37,500	\$ 12,000	\$ 119,889	312

Aircraft costing usually centers around historical weight-based power regressions, and is further variable to the quantity of aircraft produced. The development and procurement cost of aircraft, or DAPCA model attempts to correlate the cost of aircraft primarily to the aircraft empty weight, the maximum speed, and the production quantity (Large et al., 1976; Hess and Romanov, 1987). They provide a number of regressions for production components in the form:

$$C = W_{emp}^x V_{max}^y Q^z \quad (17)$$

This effort attempted to capture a large range of military aircraft, from supersonic fighters to subsonic transports, with a simple model. The speed component was included to account for changes from subsonic to supersonic regimes. In the case of SEP aircraft, the effect of speed is primarily captured by an increase in airframe weight, and not necessary to

be included. Aircraft manufacturing is typically thought of as a “made-to-order” production, implying that the cost is largely dependent on the production quantity - as much or more than the weight (Gulledge, 1986). This effect is more important for fighters and large transports, whose production can sometimes be measured by the dozen. Popular SEP aircraft are shipped from a few hundred to a few thousand per lot (five year period). Nonetheless, a cost model is pursued that accounts for the airframe weight and the production quantity.

An airframe’s cost can be distinguished into two main components. The first is the group of non-recurring costs, commonly referred to as the research, development, testing, and evaluation costs (*RDTE*). The second is the group of recurring costs, which can be thought of as the materials and labor required for each and every airframe (*ML*). While *ML* costs could be considered constant from airframe to airframe once production begins, the *RDTE* cost becomes spread across all aircraft that are sold. In an ideal world, within a production lot of Q airframes, each airframe would consist of the *ML* cost and $1/Q$ of the *RDTE* costs³, making the cost of each airframe:

$$C_{af} = ML + \frac{RDTE}{Q} \quad (18)$$

Q is the quantity shipped in the period from 2002 to 2006, according to GAMA. *ML* and *RDTE* will both be dependent on the airframe weight. Exponential functions ($A \cdot e^{bW}$) of airframe weight best represent these functions (according to the final calibration error). The model is calibrated to the SEP database. The regression error is plotted in Figure 31, and the final model is the collection of Equations 18, 19, and 20.

$$RDTE = 2678000 \cdot \exp(8.896 \cdot 10^{-4} \cdot W_{af}) \quad (19)$$

$$ML = 55731 \cdot \exp(8.403 \cdot 10^{-4} \cdot W_{af}) \quad (20)$$

³In practice, there is a learning curve during production, as bugs in the process are worked out. This effect becomes less apparent as Q increases.

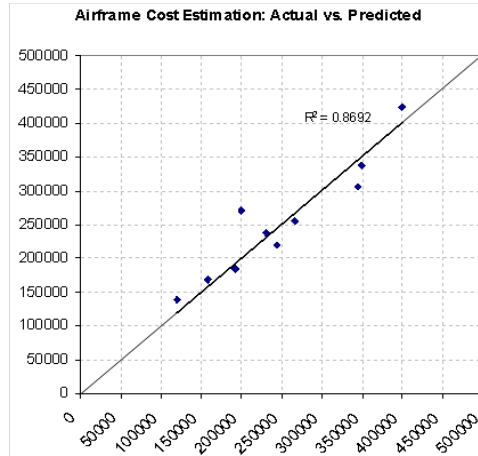


Figure 31: Airframe cost estimation regression error (\$2007).

The behavior of the model is observed in Figure 32, showing the predicted airframe cost over ranges of airframe weights and production quantities. There is no data to explicitly validate this model, but the regression error, and a seemingly reasonable behavior indicate a fair representation of the desired fleet.

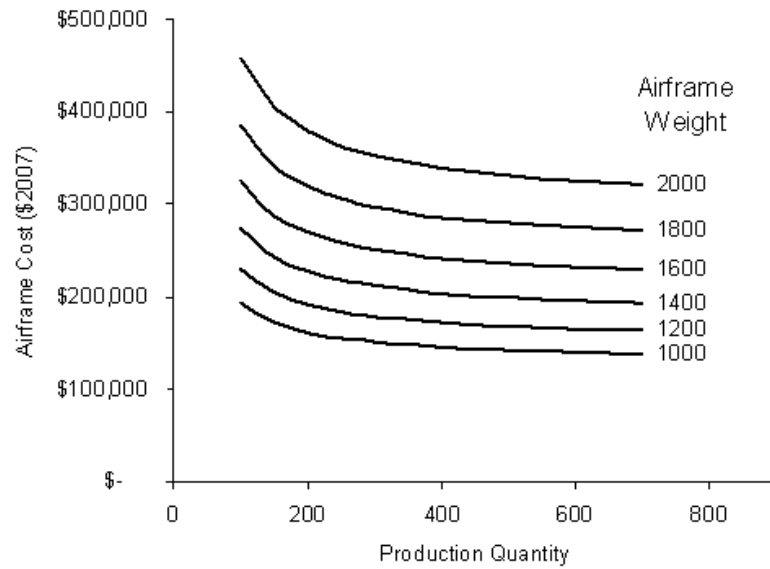


Figure 32: Airframe cost prediction model results.

4.1.4 Model Verification

When the aircraft are used as a travel mode, their performance characteristics are assumed to be those corresponding to the design mission. There is a benefit of flying at off-design conditions for the purpose of saving fuel, or extending range. In Figure 33, the off-design range is plotted against the cruise speed for two payload settings, and a constant amount of fuel. At low speeds, a large benefit is seen in range, also implying lower fuel consumption. Realistically, a traveler is more likely to fly the aircraft closer to its maximum speed - it makes the choice of GA more attractive, and it will likely meet the desired range either way. As seen in this example, the off-design payload performance benefit is less apparent as the maximum speed is approached. Thus, it seems sufficient for the purposes of this research to assume on-design performance for any given trip simulation, and focus aircraft analysis on the design and sizing aspects.

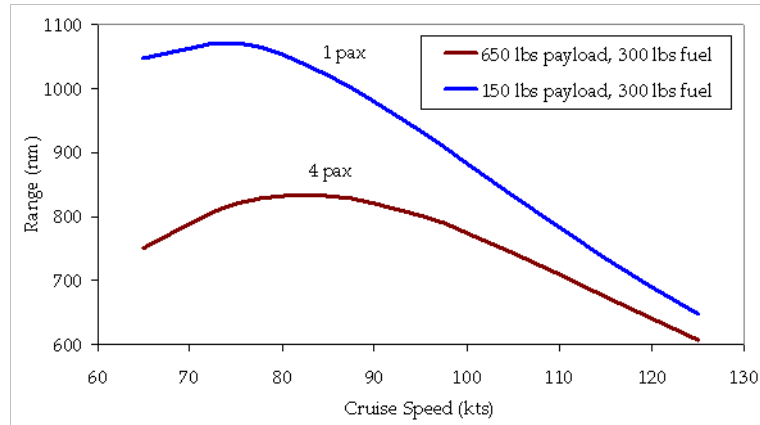


Figure 33: Cessna 172 off-design performance estimate.

The performance and cost formulations presented in this chapter are integrated to form the aircraft manufacturer model. The flow of information is represented in Figure 34.

The model is calibrated to the Cessna 172, the most common SEP. The aircraft is characterized by the fuselage flat plate drag, zero-lift drag, aspect ratio, Oswald efficiency factor, 75% and 100% brake specific fuel consumption, as well as the propeller geometry, sectional drag, and ideal loading factor, κ . Other than geometries, these values are typically not available from the manufacturer. Initial estimates are based upon a Cessna 182 Skylane

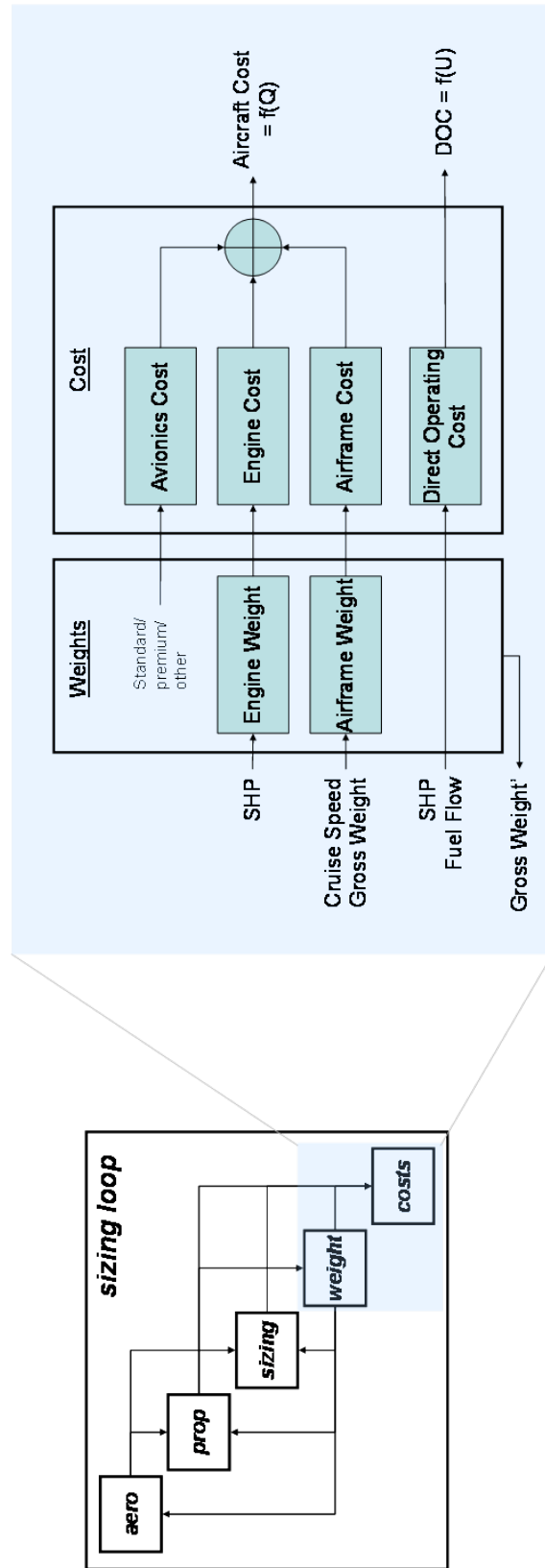


Figure 34: GAP sizing and costing information flow.

analysis by Anderson (2000), and typical rotor characteristics as found in Johnson (1994). The results of the calibration process can be found in Table 11.

Table 11: GAP performance and cost estimation calibration and verification results.

Design Mission Req'ts	Cessna 172		Cessna 152		Cessna 210		units
speed	121		106		142		kts
range	580		477		594		nm
payload	700		440		900		lbs
altitude	8000		8000		6200		ft
stall speed	48		43		54		kts

Weights and Dimensions	Actual	Predicted	Actual	Predicted	Actual	Predicted	
Takeoff	2550	2587	1670	1691	3600	3508	lbs
Empty	1550	1554	1100	1044	2254	2169	lbs
Engine	268	261	249	199	444	416	lbs
Fuel	300	332	130	206	460	438	lbs
Wing Area	174	175	160	145	174	191	sq ft

Performance							
Engine Rating	160	160	108	105	300	296	BHP
Fuel Burn	10.4	10.2	8.2	8	20.7	18.1	gph
Takeoff Ground Roll	945	951	725	682	910	1035	ft
Takeoff Over 50 ft Obstacle	1685	1691	1340	1331	1860	1675	ft
Climb Rate	720	715	715	692	988	1188	fpm

Costs							
Manufacturing Quantity	1660		N/A		110		5 years
Aircraft	\$219,500	\$224,800	\$150,000	\$161,187	\$503,000	\$462,858	2007USD
Engine	\$ 49,200	\$ 42,471	\$ 30,978	\$ 32,343	\$ 75,951	\$ 67,584	2007USD
Direct Operating	\$50/hr	\$50/hr	\$37/hr	\$40/hr	\$78/hr	\$71/hr	2007USD

After calibration, verification to non-calibrated points is desired. For this purpose, the Cessna 152 and Cessna 210 aircraft are chosen. Assuming these aircraft represent photographic scalings of the baseline, the aircraft characterization parameters remain constant. The design mission parameters of the new aircraft are input into the analysis. The results of this process are tabulated in Table 11. The ability to extrapolate from the baseline with an acceptable level of prediction accuracy is verified.

Creating a response surface also aids in the verification process by enabling the engineer to observe trends in a timely manner. Figure 38 shows the prediction profiler of the coupled GAP performance and cost models. Data from a seven variable (x-axis) full factorial design of experiments is used to estimate a quadratic response surface, which allows practically instantaneous evaluation. The prediction profiler indicates the change in responses or metrics (y-axis) along orthogonal slices passing through a selected input point (defined by hairlines). The seven input variables and the seven responses seen here are those explicitly used in the integrated analysis structure.

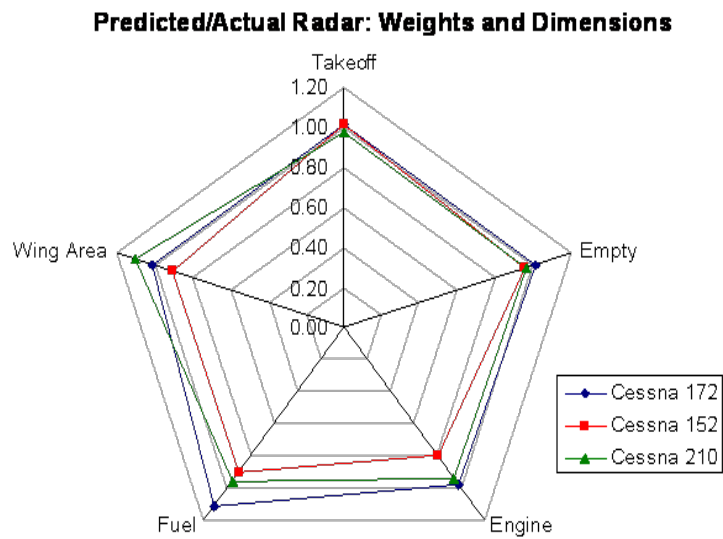


Figure 35: GAP model verification: weights.

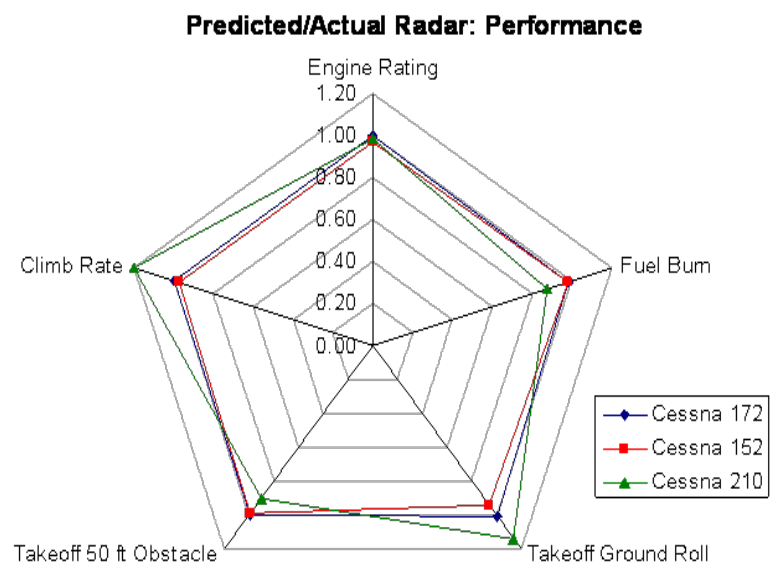


Figure 36: GAP model verification: performance.

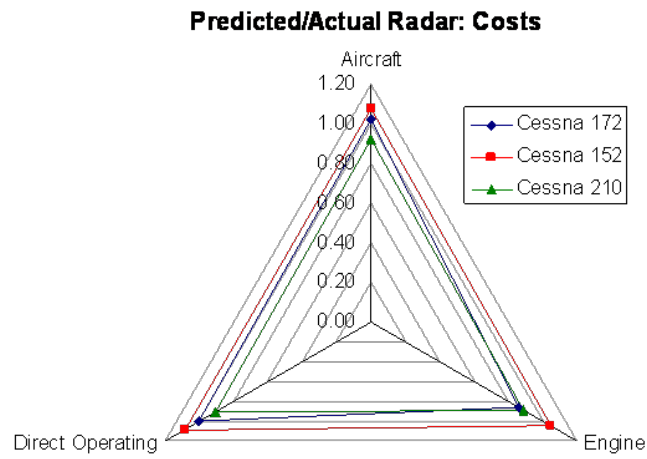


Figure 37: GAP model verification: costs.

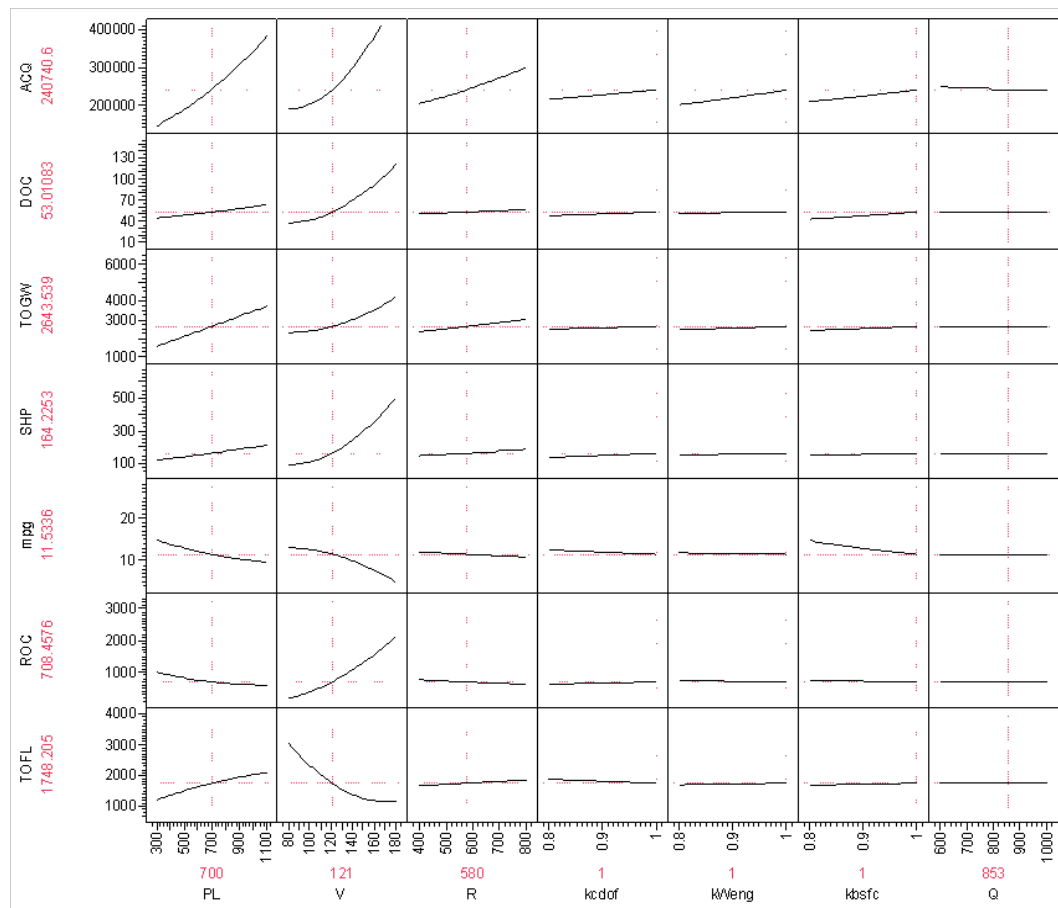


Figure 38: GAP model prediction profiler.

4.2 The General Aviation Jet

The GAJ category represents jet aircraft, more specifically twin engine, light business jets. FLOPS is used for sizing and performance analysis of GAJ aircraft (McCullers, 2001). FLOPS has been used in many commercial aircraft applications, including the design of a supersonic business jet, but few studies have focused on the validity of using FLOPS to size a GAJ, or business jet type aircraft (Briceno et al., 2002; Johnson, 1990). An effort was made to calibrate and validate FLOPS to a range of business jet designs.

While FLOPS handles much of the parametrization from dimensionless design definition, including geometry based weight regressions, the cabin and fuselage design model has not been tested for business jet configurations. The fuselage and cabin dimensional data is readily provided by the manufacturer, and from this a parametric relation to passenger capacity is sought. The passenger and dimensional data for each aircraft is found in Table 15. These aircraft are available in a variety of seating arrangements, depending on the level of luxury desired. Here, a single value was selected under which fair representation was sought, such that the number of seats corresponding to a relatively “spacious” seating configuration is used. Selection was done through visual inspection of cabin layout diagrams provided by the manufacturers, with examples as shown in Figure 39.

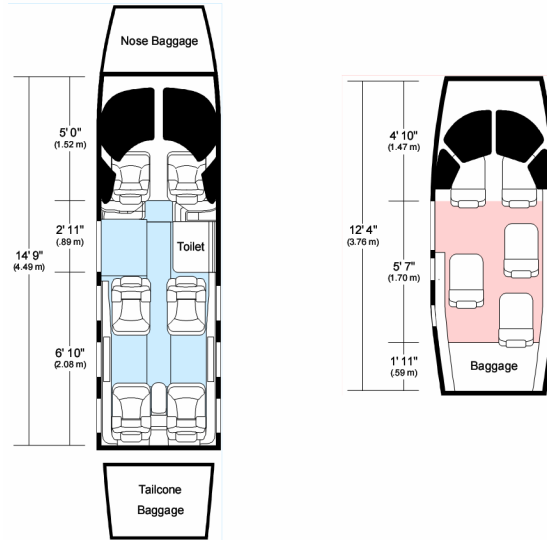


Figure 39: Seating arrangements: Mustang (left) and Eclipse 500 (right).

This collection of data is graphically represented in figures 40 and 41, showing a well-defined correlation of fuselage and cabin length to passenger seating. Notice that the Eclipse 500 has an uncharacteristically shorter fuselage than the others, due to a lack of exterior baggage compartment. The interior baggage compartment, which adds to the cabin length, adds about the same length as a toilet would, which is included on most other business jets. This is one consideration that should be actively modeled, as a trade between comfort (leg room and a reduction in “refuel” range to compliment the lack of bathroom), performance, and cost. Under this scenario, the travel demand analysis would handle the comfort factor as psychological factors and effective range, while the fuselage length formulation as used in the performance analysis would be modified to allow more passengers per length of cabin. The baseline formulas used for fuselage and cabin length parametrization, in feet, are displayed in equations 21 and 22, respectively.

$$FL = 3.6571 \cdot PAX + 24.219 \quad (21)$$

$$FL = 2.1524 \cdot PAX + 0.8286 \quad (22)$$

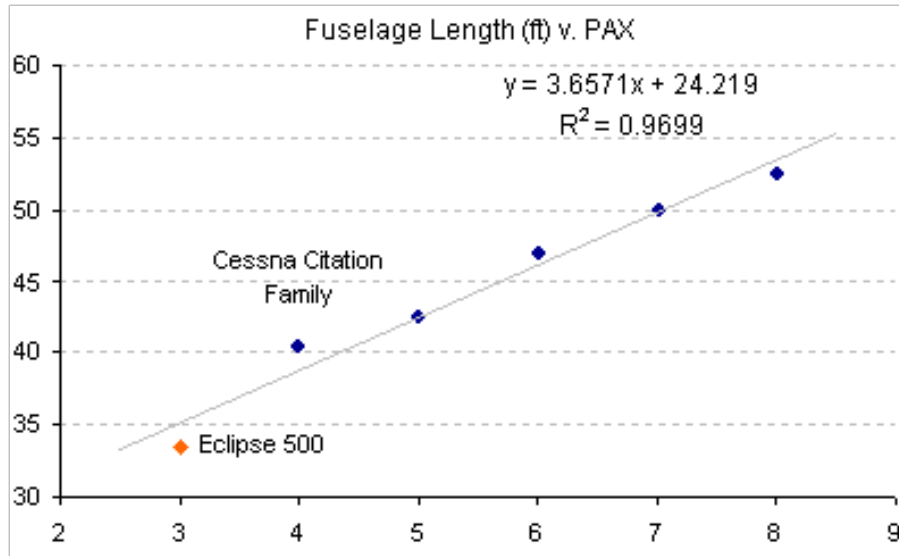


Figure 40: GAJ database: fuselage length v. pax.

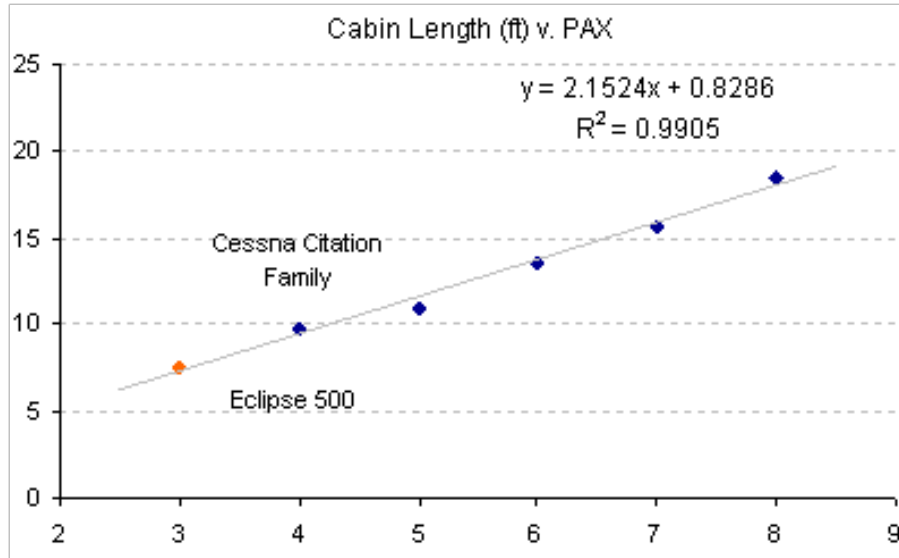


Figure 41: GAJ database: cabin length v. pax.

4.2.1 Cost Estimation

FLOPS is typically coupled with ALCCA to estimate the acquisition and operating costs of commercial aircraft, but testing showed that it could not accurately predict the acquisition cost. Thus a weight based regression of modern business jet models is used to estimate the acquisition cost, while ALCCA is used to estimate service provider related operating costs.

A GAJ database is built, which can be found in Table 12 on page 95, and utilized to create weight based regressions of the direct operating and acquisition costs. The actual costs can be found in Table 12, and are plotted against the maximum takeoff gross weight in figures 42 and 43. The plots show a reasonable correlation of the costs to the takeoff gross weight, which is often the first order estimation for costs.

The Gulfstream 450 was removed from the database as it is far outside the range of interest. Future interests in GAJ as a widespread mode lean towards the very light jet (VLJ), which helps warrant the exclusion. If its inclusion is desired, it would be more appropriate to designate a separate modeling regime for which a “large business jet” database would be created and regressed.

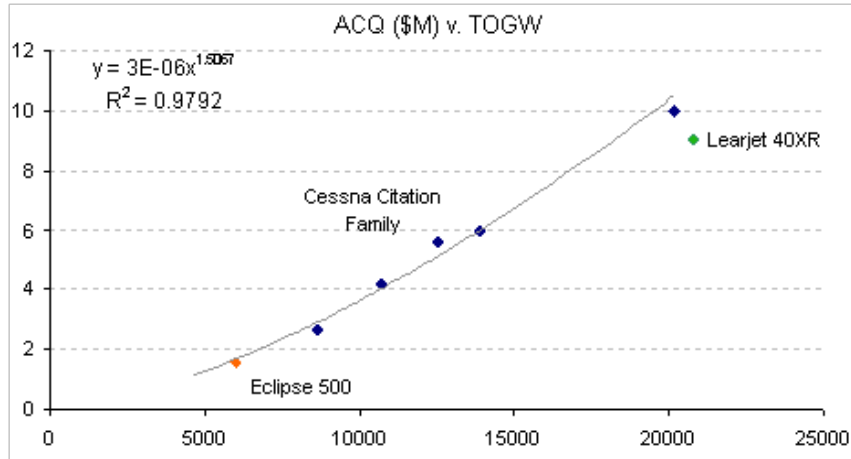


Figure 42: GAJ database (mod): Acquisition Cost v. Takeoff Gross Weight.

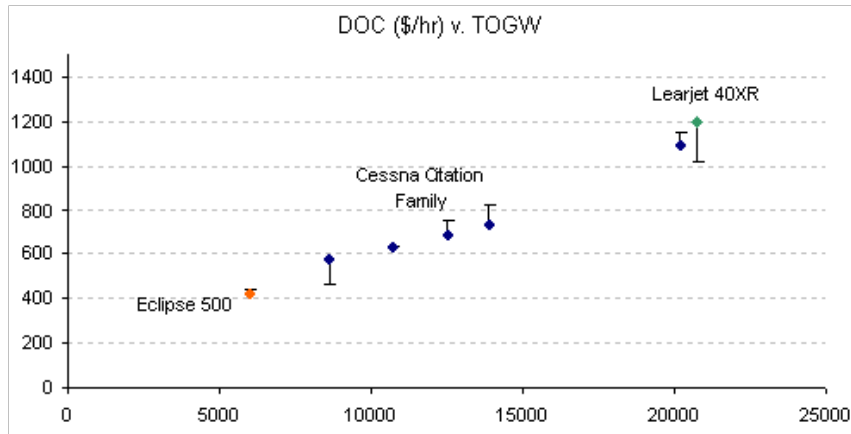


Figure 43: GAJ database (mod): Direct Operating Cost v. Takeoff Gross Weight.

The regression of direct operating cost is also modified to incorporate known values of fuel burn and fuel cost. The direct operating cost is assumed to be a function of the cost of fuel burned and maintenance. The cost of fuel burned is the product of fuel flow, FF , in gallons per hour, and fuel cost, $COFL$, in dollars per gallon. Maintenance costs are assumed to be a function of $TOGW$, for which a power regression is used.

The formulas which are used to predict GAJ costs are displayed as equations 36 and 37, in \$M and \$/hr, with weight input in lbs. The error bars in Figure 43 indicate the predicted values of DOC using Equation 37 with known fuel flow values and \$3/gal fuel cost.

Table 12: Business jets representing the GAJ database, with 2007 shipments and costs.

Shipments and Costs	2007 Shipments	Rank (2007)	Acquisition Cost (\$M)	Operating Cost (\$/hr)
Mustang	45	11	2.7	580
CJ1+	34	16	4.2	635
CJ2+	44	12	5.6	689
CJ3	78	4	6.0	733
XLS+	82	2	10.0	1091
Eclipse 500	98	1	1.6	425
Learjet 40XR	57	7	9.0	1200
Gulfstream GS450	79	3	41.5	3234

$$ACQ = 0.000003 \cdot TOGW^{1.5067} \quad (23)$$

$$DOC = 0.0777 \cdot TOGW^{0.814} + FF \cdot COFL \quad (24)$$

4.2.2 Model Verification

In 2007, the VLJ⁴ market emerged with the Eclipse 500 grabbing the number one shipped jet aircraft that year, from just a single shipment the year before. The Cessna 510 Mustang, another VLJ, also began significant shipments. The VLJ, and especially its use as an air taxi, is seen as the most relevant topic for the study of future air transportation. A parametric representation of the VLJ and light jet performance and cost is desired, so as to see the phenomena and sensitivity to requirements and design changes.

The Cessna Mustang is used as the calibration point, and a handful of the most popular business jets are used as a verification population. While the Eclipse 500 is the more popular VLJ, the Mustang is chosen because it is part of a family of business jets, the Cessna Citation. The Citation family is the most popular, in terms of shipments, and the most diverse, with a wide range of mission capabilities. Cessna (2005*a,b,c,e,d*) also provide the most comprehensive and consistent publication of performance and mission data, facilitating model creation and verification. The GAJ database, along with the number and rank of 2007 shipments, is shown in Table 12 (GAMA, 2008).

⁴Primary to the definition is single pilot operation and under 10,000 lbs gross weight.

At the core of the database is the Citation family, laying a solid foundation for a parametric representation. Additionally, several other well-known manufacturers are represented, with the individual aircraft chosen based on the highest ranking in shipments⁵. These aircraft include the Eclipse 500, the Learjet 40XR, and the Gulfstream 450 (Eclipse, 2007*a,b*; Bombardier, 2008; Gulfstream, 2008).

FLOPS is calibrated to the Cessna Mustang, using the aircraft and mission definitions found in Table 13. The sizing option is used, and fuel reserves for a 200 nm alternate airport cruise are included in the mission. Additionally, FLOPS internal weight and aerodynamics routines were used. The results of calibration are displayed in Table 14.

Table 13: Cessna Mustang aircraft and design mission definition.

Aircraft Definition	
cabin length (ft)	9.8
overall length (ft)	40.5
fuselage diameter (ft)	4.6
Horizontal Tail Area (sq ft)	58
Vertical Tail Area (sq ft)	38
Engine Deck	FJ44
TWR	0.338
Wing Loading (lbs/sq ft)	48.8
Aspect Ratio	9.0
Design Mission	
Range (nm)	950
Speed (kts)	340
PAX	4

Table 14: Cessna Mustang actual and predicted metric values.

	Actual	Predicted	% error
design fuel (lbs)	2215	2221	-0.3%
TOGW (lbs)	8645	8657	-0.1%
Tsls (lbs)	2920	2924	-0.1%
empty weight (lbs)	5550	5556	-0.1%
TOFL (ft)	3110	3119	-0.3%
ACQ (\$M)	2.7	2.7	-1.8%
DOC (\$/hr)	580	539	7.6%

⁵While total sales in billings is arguably preferable to sales quantity, due to large differences in sales price, the former was not readily available by make and model.

Next, verification across the GAJ database is sought. Geometry and design mission information are collected for all aircraft, translated to the appropriate FLOPS input values, executed in sizing mode, and verified by weight and cost. Tables 15 and 16 summarize the geometry and design values, most found directly but some indirectly through reverse engineering where necessary. The geometry is defined in FLOPS by the cabin length, fuselage diameter, fuselage length, aspect ratio, and the horizontal and vertical tail volume coefficients. The design characteristics are defined by the wing loading and the thrust to weight ratio. All aircraft utilize the same engine deck, modeled after the FJ44, sized by FLOPS to the appropriate thrust rating. The design mission is defined by the number of passengers (220 lbs each including baggage), the cruise Mach number, and the primary mission range. To the primary mission, a post 200 nm alternate airport mission is added, corresponding to the NBAA IFR range, used in the majority of the manufacturer's published data.

The results of the verification runs are presented graphically in Figure 44, in the form of an actual by predicted plot for takeoff gross weight. The results show reliable approximation within the range of missions defined by the aircraft in the database.

Table 15: GAJ database geometry definition.

Dimensions	cabin length (ft)	fuselage diameter (ft)	overall length (ft)	wing span (ft)	average chord (ft)	wing area (sq ft)	Horizontal Tail Area (sq ft)	Vertical Tail Area (sq ft)
Mustang	9.8	4.6	41	43	4.8	177	58	38
CJ1+	11.0	4.8	43	47	5.2	219	71	49
CJ2+	13.6	4.8	47	50	5.6	256	79	56
CJ3	15.7	4.8	50	53	5.9	277	80	61
XLS+	18.5	5.7	53	56	6.3	403	129	103
Eclipse 500	7.5	4.9	34	38	3.7	114	38	27
Learjet 40XR	18.0	5.5	56	48	7.5	312	84	69
Gulfstream GS450	45.0	8.0	89	78	11.5	841	250	200

Table 16: GAJ database design values.

Design Values	Thrust to Weight	Wing Loading (lbs/sq ft)	empty weight fraction	Aspect Ratio	HT Volume Coefficient	VT Volume Coefficient
Mustang	0.338	48.8	0.64	9.0	3.0	1.9
CJ1+	0.367	48.8	0.64	9.0	2.8	1.9
CJ2+	0.398	48.8	0.63	9.0	2.7	1.9
CJ3	0.407	50.1	0.62	9.0	2.6	2.0
XLS+	0.408	50.1	0.63	9.0	2.5	2.0
Eclipse 500	0.300	52.6	0.64	10.3	3.4	2.4
Learjet 40XR	0.337	66.6	0.67	6.4	2.1	1.7
Gulfstream GS450	0.375	87.9	0.58	6.8	2.4	1.9

Table 17: GAJ database engine data.

Propulsion	engine	Tsls (lbs)
Mustang	PW615F	2920
CJ1+	FJ44-1AP	3930
CJ2+	FJ44-3A-24	4980
CJ3	FJ44-3A	5640
XLS+	PW545C	8238
Eclipse 500	PW610F	1800
Learjet 40XR	TFE731-20-BR	7000
Gulfstream GS450	Mk 611-8C	27700

Table 18: GAJ database design mission requirements and weights.

Design Mission and Weights	pax	speed (ktas)	mach	range (nm)	payload (lbs)	TOGW (lbs)	OEW (lbs)	fuel (lbs)
Mustang	4	340	0.59	950	880	8645	5550	2215
CJ1+	5	389	0.68	1050	1100	10700	6890	2710
CJ2+	6	418	0.73	1100	1320	12500	7895	3285
CJ3	7	417	0.72	1350	1540	13870	8640	3690
XLS+	8	440	0.76	1550	1760	20200	12800	5640
Eclipse 500	3	370	0.64	900	660	5995	3829	1506
Learjet 40XR	7	432	0.75	1500	1540	20776	13861	5375
Gulfstream GS450	16	459	0.80	4000	3520	73900	43000	27380

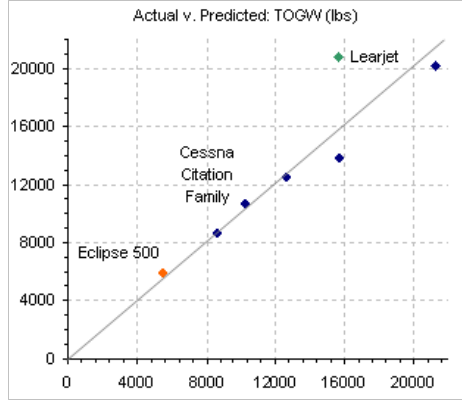


Figure 44: GAJ database: actual v. predicted: TOGW.

Finally the model behavior is verified through a prediction profiler of a quadratic response surface model, fit to a 2,071 run central composite design of experiments. A static view is displayed in Figure 45. For these runs, the fuselage is sized using the method in the following section.

4.2.3 Optimization

Because each set of mission requirements under consideration will be optimally performed with a particular set of design variables, an optimization routine is added to the GAJ sizing analysis. The optimization problem is as follows:

minimize: takeoff gross weight,

by varying: aircraft geometry and design characteristics,

while satisfying: mission design requirements.

The aircraft geometry is represented by the wing aspect ratio, taper ratio, and sweep, and the design characteristics by the wing loading and thrust to weight ratio. The mission design requirements are represented by the number of passengers, range, and speed of design mission, as inputs to the sizing process. Additionally, design requirements of takeoff field length, approach speed, and climb rate, at ISA conditions and design TOGW, are implemented as optimization constraints. The approach speed is a hard constraint defined by the

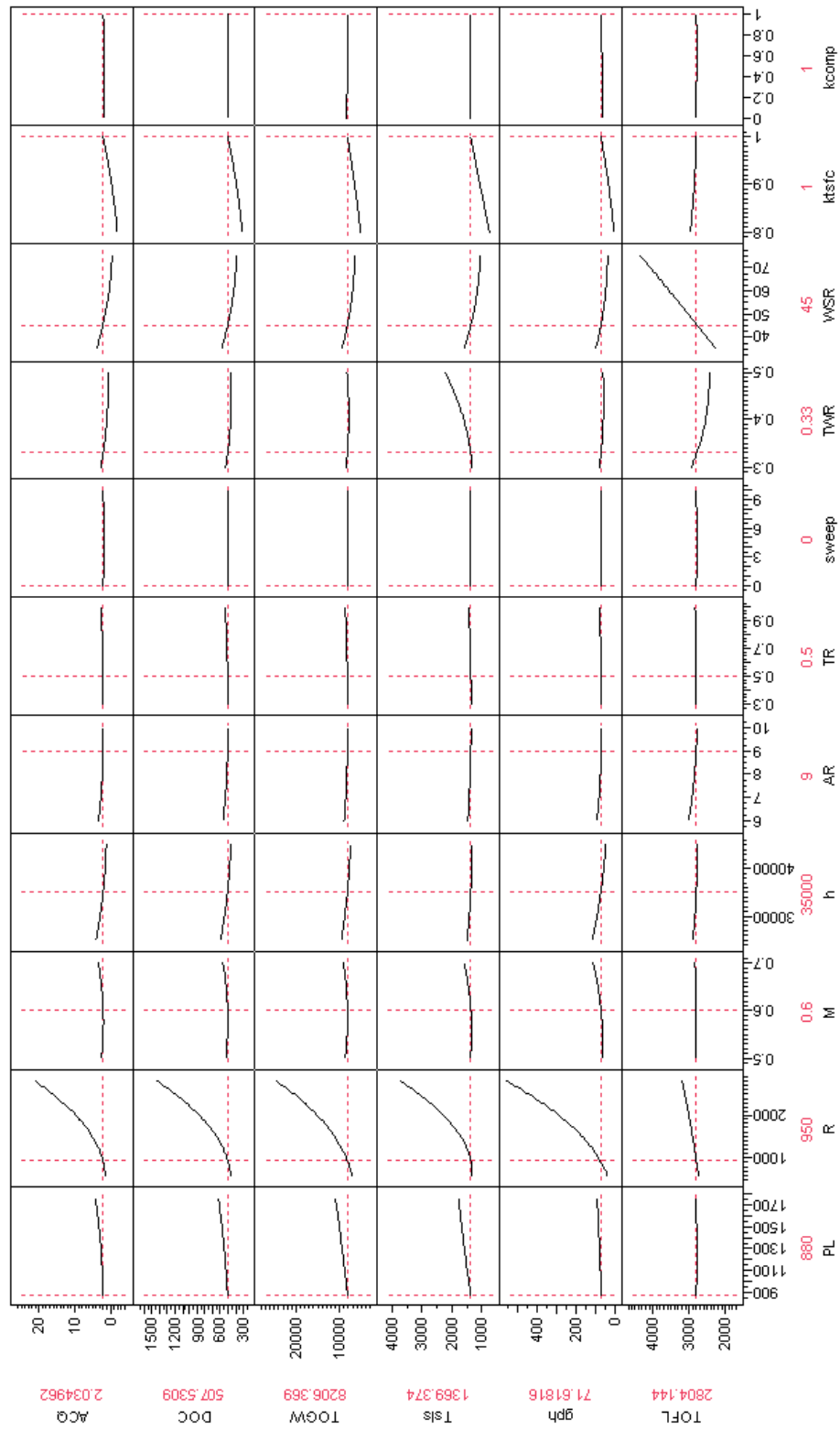


Figure 45: GAJ model prediction profiler via RSE.

FAA, typically defined as 79 ktas. The climb rate also has hard requirements defined by the FAA, but it is a fairly low requirement and the customer desire would be more stringent, although likely superseded by the takeoff field length requirement.

The takeoff field length constraint can be thought of as an accessibility requirement; a shorter takeoff field length corresponds to shorter door-to-door travel time, and vice versa. While this statement is not as straight-forward to implement as it might sound, due to location specific geography, a loose correlation could be made by observing the cumulative distribution of available public runways as function of the field length, as depicted in Figure 1.

It is interesting to note that the majority of SEP aircraft, being able to takeoff in less than 2,000 ft, have practically all runways available to them. On the other hand, larger jet aircraft have takeoff field lengths corresponding to the area of greatest decline in availability, indicating that an active tradeoff should be expected. For example in considering a design tradeoff from a 3,000 and 4,000 ft takeoff field length capability, the loss of approximately 1,500, more than 20%, of public runways must be accounted for. This would be done by estimating ingress and egress time changes based upon the average availability, although an accurate model would be difficult to create without location specific information.

Chapter V

GA TRAVEL DEMAND MODELING

The theory of travel demand is well documented and has been under development since the 1950s. A general treatise of travel demand theory can be found in McCarthy (2001), Glaister (1981), and Bates (2000). The study of travel demand includes modeling the volume of trips demanded by a population and can also include the demand for ownership of a particular travel mode. In this study, estimating the latter is of key importance, as it is what drives the production of an aircraft, although the former is equally important for providers of travel services.

The demand for travel has its roots in the spatial separation of people, goods, and activities. The modeling of travel demand implies the prediction of individuals' and populations' desires to transcend this separation, and answer questions of if, when, and how to do this, given the "cost" of each alternative method. Identifying the "cost" of each alternative is not simply finding the ticket price of each alternative. Consumers put differing values on their time, put aside varying amounts of time and money for travel, have varying levels of travel services available to them, and possess a host of unobservable variations in preferences.

The most common transportation demand modeling concept is known as the four stage model: 1) trip generation, 2) trip distribution, 3) modal split, 4) assignment. Realistically, all steps have some level of interaction, and cannot be separated. In practice, the level of feedback is dependent on the desired level of detail. Bates summarizes the four steps, each by an intuitive question to be answered: "How many travel movements will be made, where will they go, by what mode will the travel be carried out, and what route will be taken?" (Bates, 2000).

Stages one and two are typically carried out by referring to historical data. Extrapolation from historical trends is typically done by regression of a parametric model, such as the gravity model, that typically takes into account the socioeconomic characteristics and

distance between each pair of origin and destination locations. Socioeconomic characteristics of a location, e.g. average income, will drive the volume of demand generated, and the distance and socioeconomic characteristics of surrounding locations will drive the selection of destinations. Once consumers have a destination, they assess the choice of modes which can take them there. A systematic decision making method for the consumers is needed for this stage. The following section provides an explanation of utility, the basis for consumer decision making in *Mi*. Finally, assignment determines the specific physical route that is taken, and can include route optimization.

5.1 Mode Utility

One of the underlying ideas of travel demand, or any economic demand theory, is the idea that consumers can systematically place a value of utility on their alternative choices. This train of thought leads to the *utility function*, which is essential during mode choice or modal split. The utility function defines the balancing of benefits and costs of any travel mode within the perspective of the users. It has been applied on varying levels of granularity, from the choice of an individual considering a single trip to a bulk modal split of an entire county over a one year period. In this research, the utility function is applied by each consumer for each trip. Mode *utility* is typically defined as the *negative of disutility*, which is a summation of all the “costs” associated with a mode, according to the consumer. The utility of a transportation mode m , over a single trip j , for consumer i , is represented in Equation 25.

$$U_j(m) = -\alpha (c_i C_j(m) + t_i T_j(m) + n_i N_j(m)) \quad (25)$$

C_j , T_j , and N_j are the monetary cost, en route time, and nuisance values respectively of trip j . The cost and time are directly measurable values, whereas the nuisance represents the unobservable and primarily qualitative aspects that influence a traveler’s decision. c_i , t_i , and n_i are the individual’s relative weighting factors for each of the utility components.

The nuisance factors, N_j and n_i - the factors that make human decision making seemingly erratic at times - are not measurable, thus the cost and time terms are isolated and grouped

to form the *systematic utility*, defined in Equation 26.

$$V_j(m) = -\alpha(c_i C_j(m) + t_i T_j(m)) \quad (26)$$

For each trip and mode of travel, the traveler then has a deterministic quantity of utility. The erratic nature of the selection process is accounted for in the choice model. Rather than deterministically selecting the mode of greatest utility, each mode takes on a probability of being selected - the probability being a function of its systematic utility.

The demand for usage of GA is predicted utilizing the code *Mi*, developed in Lewe (2005). *Mi* is notably distinguishable from other routines by the use of agent based modeling (ABM), a technique in which populations of agents, each assigned a unique set of behavioral aspects, conglomerately simulate a large-scale process, bringing out high-level emergent behaviors. In the case of *Mi*, a population of traveling agents, mirroring the population of US travelers, individually create travel agendas and make travel mode choices based on their unique characteristics, primarily defined by their income, locale, and household or enterprise size. Refer to Section 2.3 for additional descriptions of the model, and comparison of other available codes.

Referring to modeling sub-questions and hypotheses 1.2-1.6, found in Section 3.2, *Mi* will require some additional functionality. These functionalities are developed for the purpose of the present research, and presented as the focal points of this chapter. In summary, these functionalities are: aircraft ownership decision models; service-based demand location selection, spatial distribution, and temporal distribution; and enhanced market differentiation detail.

5.2 *Fleet Ownership Models*

The GA fleet consists of multiple aircraft types as well as multiple types of ownership. Year 2005 statistics are shown in Table 19, where the primary use categories have been truncated to include only travel categories, and the aircraft type have been truncated to include only powered fixed wing, certified aircraft (GAMA, 2006b).

Table 19: GAMA fleet by type and primary use.

Aircraft Type	Total Active	Personal	Business	Corporate	Air Taxi ²
Piston Total	167,608	121,295	21,371	2,012	2,651
One-Engine	148,101	112,105	15,780	719	1,169
Two-Engine	19,412	9,166	5,591	1,293	1,465
Other Piston	95	25	0	0	17
Turboprop Total	7,942	1,300	1,868	2,372	1,256
One-Engine	2,595	557	715	222	444
Two-Engine	5,307	743	1,153	2,150	812
Other Turboprop	40	0	0	0	0
Turbojet Total	9,823	720	834	5,508	2,025
Two-Engine	9,097	649	806	5,004	1,939
Other Turbojet	727	71	28	505	87

The original fleet determination in *Mi* is pre-assigned through a probability of ownership, where each agent was assigned ownership if a randomly selected value was within a fixed probability of ownership, $p(own)$. The probability of ownership was based on the historical statistical probability that an agent's enterprise class or household type had ownership. The primary shortfall of this method is that ownership will remain the same regardless of an aircraft's cost and performance, or socioeconomic conditions - unless the user specifies otherwise.

In this research, three categories of ownership have been identified: corporate, non-corporate, and charter/rental. In the simulation, separate ownership prediction methods are used for each of the three categories. Coincidentally, the methods also represent different levels of ownership prediction complexity, which will be explained in the respective sections.

Mi handles two alternative aircraft types, the GAP and GAJ, whereas in reality there are a larger number of types, including rotorcraft, balloons, and turboprops. One question which arises when it is necessary to reduce the detail of statistical data: consolidate or truncate categories? Each choice has its own shortfalls. If data is consolidated, i.e. similar

categories are grouped into a single category, then specific trends might be lost about a subgroup which may be of particular interest. For example, the GAJ category was originally defined to consist of multi-engine piston and all turbine powered aircraft. But, the resulting representative aircraft - an average of these types - fell in to “no-man’s land”. That is, it was not fast enough to capture the jet market, and was too expensive to capture the piston market. On the other hand, when data is truncated, a risk is run in which interaction from an excluded group is not accounted for, and results and trends become misleading.

So far, the author has experienced that truncation is the favorable option. First, because truncated categories can be added as time allows, without modification to already modeled categories. Secondly, if results due to truncation are suspicious, they can be fixed by adding truncated categories, otherwise they are more reliable than those from an “averaged” consolidated category. For the purposes of calibration, the GAJ category is defined to include multi-engine piston and all turbine powered fixed wing aircraft, although in retrospect, the more appropriate choice would have been to define GAJ as only turbojet aircraft, and temporarily exclude the other categories. The GAP category is defined to include only SEP aircraft.

5.2.1 Corporate

Corporate ownership is defined by individual or group business transportation with a paid flight crew, either owned or fractionally owned by the firm. This category is dominated by turbojet aircraft, i.e. the corporate jet, making up approximately 56% of the fleet. By count, this may not seem like a dominating value, but considering the cost of a typical corporate jet (order of 10-40 \$M) to that of a twin piston or turboprop (order of 1 \$M), there is a clear preference. There are approximately 9,173 GAJ corporate owners, and 719 GAP corporate owners.

A firm may consider corporate ownership if they determine that the utility of owning the aircraft is better than the utility of all other options. The utility has two sources: first the cost and performance of the aircraft, and second the characteristics of its usage and users. The usage and user characteristics are variable to the type and size of business - who

uses the aircraft and why, and the opinions of those in charge, to begin the list. A complex implementation within *Mi* would require that a population of enterprises be created, each of which would determine, based on its simulated characteristics, the utility of corporate ownership. This would be a difficult task, especially considering that calibration data would be difficult to acquire. A simple, yet cost sensitive model is implemented and explained here for the estimation of corporate ownership.

The model is based upon estimates of the probability that a given firm owns an aircraft, $p(own)$, and the probability that a given employee in that business has access to the use of the aircraft, $p(access)$. The annual sales of the firm are also considered when determining $p(own)$. $p(access)$ is based on an estimate of the number of employees that have access to the aircraft, divided by the number of employees. Finally, the probability that a given agent has access to a corporate aircraft for travel purposes is the combined probability that their business owns the aircraft, and they are privileged to use that aircraft, $p(own)$ and $p(access)$.

The US Census Bureau categorizes firms into five classes, based upon the annual sales or receipts. The class structure can be seen in Table 20, where a firm is in the maximum class for which the minimum sales criteria is met. In *Mi*, each agent traveling for business purposes is assigned an employer whose class is determined from a probability distribution corresponding to the distribution of employees in columns three and four of Table 20. This portion of the process was originally implemented in *Mi*; the following explains the current modification.

Table 20: Firm categories and characteristics.

Firm Characteristics			
Cat	Average Annual sales (\$M)	Average No. Employees	# Firms
V	4020	19,143	1097
IV	265	1,795	7,743
III	25.1	167	90,201
II	2.73	28	704,535
I	0.256	4.4	3,807,253

Corporate ownership by GAMA is only specified as an aggregate value, rather than by firm class, and thus an assumption is made: the probability that a firm of a given class will possess corporate ownership is dependent upon their annual net sales (S) divided by a reference aircraft price (ACQ). Further, $p(own)$ moves toward 0% as $\frac{S}{ACQ}$ approaches zero, and asymptotically approaches 100% as $\frac{S}{ACQ}$ approaches infinity. A logistic function achieves the desired behavior, and is used in the following form:

$$p(own) = \frac{1}{1 + a \cdot \exp(-b \cdot \log(\frac{S}{ACQ}))} \quad (27)$$

For the purpose of calibration, the fleet size of a given class is the product of the number of firms in the class and $p(own)$, defined above. S is defined as the average sales among the class, and ACQ is the acquisition price of the baseline GAP and GAJ aircraft. The total fleet is the sum of all class fleets. The total fleet size is known, as published by GAMA, and is thus used to help calibrate $p(own)$.

Calibration of the GAJ model was performed first. The function defining $p(own)$ requires calibration of two constants, requiring another assumption: 99% of class V firms possess GAJ corporate ownership¹. $p(own)$ for GAJ corporate ownership is calibrated to the GAMA total fleet size, and the function is graphically represented, along with the specific predicted class values, in Figure 46. The fleet size of each class is seen in Figure 47, where it is seen that even though $p(own)$ is much higher for class V, class III and class IV have larger fleets due to the total number of firms.

The GAP category has a much smaller corporate presence, likely due to the lack of speed and comfort necessary for use by highly paid, widely traveling executives. $p(own)$ for GAP is left as constant, although varying among classes. After assuming that $p(own)$ of class V to be zero, the remaining classes are calibrated such that the total GAP corporate fleet size is met. The final fleet size of each class is seen in Figure 47.

¹Notice that class V firms average net sales of over \$4B and employ over 19,000 people.

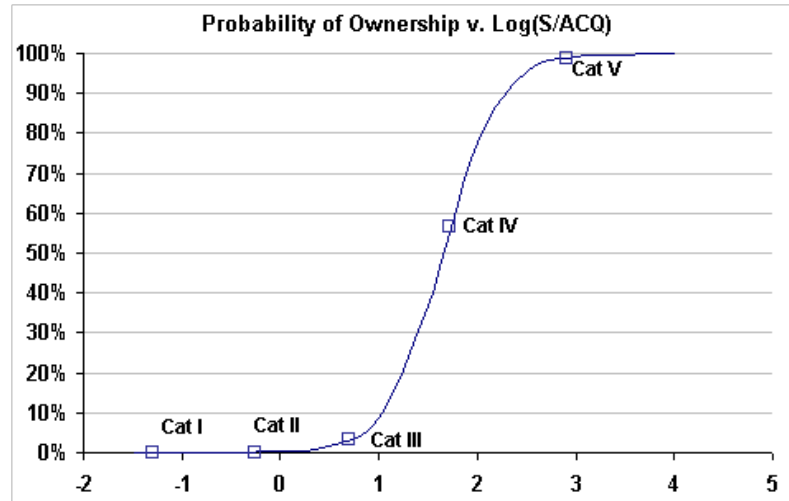


Figure 46: GAJ corporate ownership probability function.

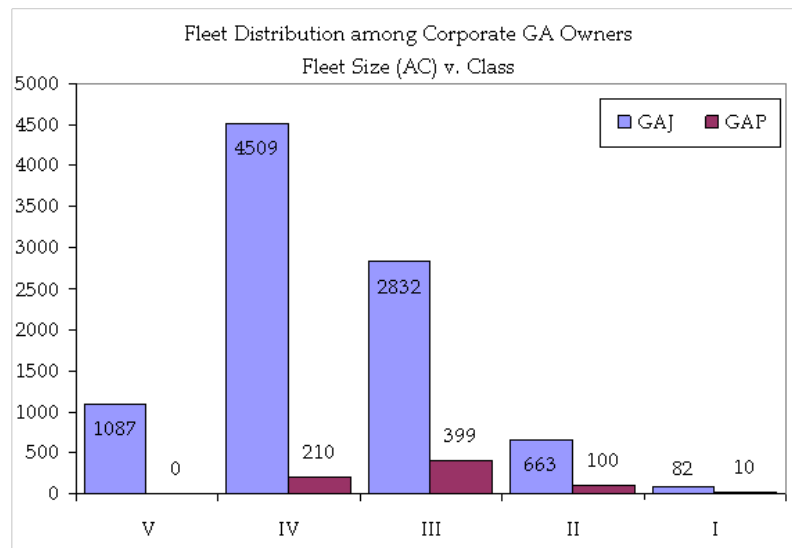


Figure 47: GAJ and GAP fleet distribution by firm class.

With the probability that an agent's employer possesses corporate ownership determined, the probability that the employee has access for any given business trip is estimated next. By definition, a corporate jet is flown by a hired crew, and thus potentially any company employee could use the aircraft. In reality, access is limited to a small fraction of the employees, likely the group of executives whose time and presence is of very high value. $p(access)$ is estimated by dividing the estimated number of employees with access in the

firm by the total number of employees. The former quantity is not easily known and must be estimated. The latter quantity is taken as the average number of employees for each firm class. The estimated values of $p(access)$ are found in Table 21, under employee access. Finally, for a given agent the probability that a corporate owned aircraft is an alternative in their mode choice model is found by the product of $p(own)$ and $p(access)$. Values of $p(own)$, $p(access)$, and the product of the two are found in tables 21 and 22.

Table 21: Corporate GAJ ownership and access probabilities.

Firm	GAJ Ownership			Employee Access		Total
Cat	p(Own)	Fleet (AC)	Fleet (%)	# Emps w/access	p(Access)	p(Own) & p(Access)
V	99%	1087	12%	50	0.26%	0.258770%
IV	58%	4509	49%	20	1.11%	0.648748%
III	3.1%	2832	31%	3	1.79%	0.056274%
II	0.094%	663	7%	2	7.19%	0.006761%
I	0.002%	82	1%	2	45.60%	0.000985%
	Total:	9173	100%			

Table 22: Corporate GAP ownership and access probabilities.

Firm	GAP Ownership			Employee Access		Total
Cat	p(Own)	Fleet (AC)	Fleet (%)	# Emps w/access	p(Access)	p(Own) & p(Access)
V	0.000%	0	0%	50	0.26%	0.000000%
IV	2.712%	210	29%	20	1.11%	0.030216%
III	0.442%	399	55%	3	1.79%	0.007927%
II	0.014%	100	14%	2	7.19%	0.001020%
I	0.000%	10	1%	2	45.60%	0.000120%
	Total:	719	100%			

This model adds an element of cost to the corporate ownership estimation, but lacks inclusion of the performance aspects of the aircraft. A more accurate utility based ownership model would require a long term aggregation of the aircraft's utility, which inherently includes the performance aspects. Evaluating the utility of ownership for a firm is seen as considerably more complex than for an individual user. So, although it is not done for corporate ownership, it is done for personal, or non-corporate ownership, explained in the following section.

5.2.2 Non-corporate

The fleet of aircraft under the personal and business GAATA primary use categories contribute to the non-corporate ownership. In 2005, this fleet consisted of 127,885 single engine pistons, or GAP aircraft, 14,757 multi-engine pistons, 3,168 turboprops, and 1,554 turbojets, or 19,479 GAJ aircraft. This fleet weighs heavily towards the GAP category, approximately 87% of the fleet. In the GAJ category, the makeup is dominated by twin piston aircraft. These numbers imply that these owners weigh the cost of the aircraft more heavily than corporate ownership, perhaps even contributing disproportionate amounts of their income due to their enthusiasm for flight. For the purposes of simulation, these aircraft could be utilized for both business and personal use. Owners in these categories pilot these aircraft without a hired crew. This is by definition in the case of the business category.

The Utility of Ownership

According to Bates, the utility of car ownership is a function of 1) the differential accessibility associated with car ownership, 2) the costs associated with car ownership and use, 3) the basic travel demand due to household structure, with license-holding as a prerequisite, and 4) available income. Many intricacies can be accounted for in the model², but because of the empirical nature, intricacy should follow the volume of evidence available. Due to limited supporting data, a model capturing the main effects, most typically time and cost when travel is concerned, is pursued.

An existing model, presented in 1998 as part of the NASA General Aviation Propulsion Program, attempts to predict the demand for GA aircraft as a function of new license-holders, the price of an aircraft, and the national mean income. This model is summarized in Figure 48.

While the model is intuitively appealing, the use of new pilots as a determination for sales is questionable, as there is no evidence to suggest that only new pilots seek to purchase an aircraft, and it seems just as likely that an experienced pilot will be seeking to purchase an aircraft, possibly after reaching a sufficient income level. More importantly, this model

²See Bunch (2000) for a summary of details and general techniques that could be considered in an ownership model .

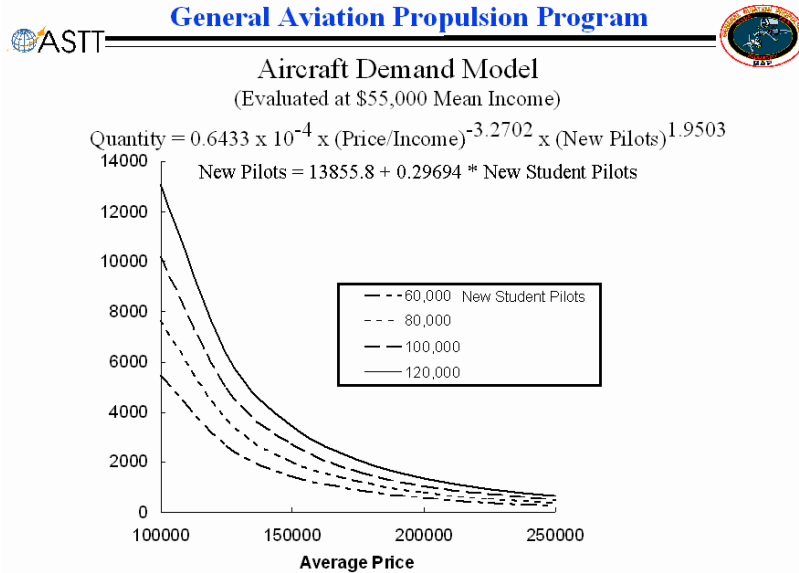


Figure 48: NASA aircraft demand prediction model NASA (1998).

does not capture certain aspects of the utility of ownership, namely the performance and cost of operation, and how these aspects compare to other available modes. One could argue that these aspects are not necessary because 1) the average GA aircraft has remained relatively constant in performance and cost and 2) the population of owners are dominated by enthusiasts whom purchase the most affordable aircraft as long as it meets a performance threshold. This may be true of current trends, but the objective of this research is to explore the possibilities in a variety of scenarios, some of which may transcend the trends of history. Thus, it is desired to bring the model a few steps forward and capture to some degree each of the four characteristics claimed to influence car ownership.

In line with demand theory, a consumer will own a vehicle, in this case an aircraft, if the utility of owning it exceeds the utility of not owning it, defined as zero. A fully encompassing model must assess the ownership of each mode individually, as well as all the combinatorials of modes and fleet size. For example, a consumer could hypothetically decide to own two cars, a single engine piston, and a jet aircraft while another consumer only owns one car. The ownership model in this analysis has only two alternatives, own or do not own.

Before ownership is considered, consumers should first meet a set of criteria. Three criteria have been identified as follows:

1. Consumer is a licensed pilot;
2. Consumer income to aircraft price ratio is sufficient;
3. Aircraft carrying capacity is sufficiently large in relation to household size;

The term “sufficient” implies that some level of variation will occur from household to household, and thus the limit is set as a soft, probabilistic constraint. Step two and three are prescreening criteria, simply to reduce the number of analyses required. Step two eliminates households which definitely cannot afford to own an aircraft, and step three eliminates large households from considering a very small aircraft, because it will rarely be utilized. If a consumer meets these criteria, an ownership utility function is defined to make the choice of ownership. The ownership utility function, $V_{m_{own},i}$, consists of two components:

1. The aggregate of trip-specific utility gained through operation, which accounts for the mode’s direct operating costs and en route time, relative to the next best alternative;
2. The disutility associated with ownership, including acquisition cost, indirect operating costs, and time spent managing the aircraft.

The first component refers to the utility of using the owned mode, m_{own} , in relation to the next best mode, in each trip taken where the owner decided to use m_{own} . If on a given trip j , m_{own} is chosen and utilized, then all modes are ordered by systematic utility as $m_1, m_2, m_3 \dots m_N$. If $m_1 = m_{own}$, then the relative utility of m_{own} for that trip is $V_j(m_1) - V_j(m_2)$. In other words it is the utility gained by having m_{own} available when the consumer might otherwise use the next best alternative, m_2 . Note that because the mode selection is done via a probabilistic discrete choice model, it is possible for m_{own} to be chosen, but not have the greatest systematic utility. In this case, the relative utility is zero. Over all trips j in a given time period, the aggregate utility of ownership for mode m_{own} is:

$$B_{m_{own},i} = \sum_{j, m_{choice}=m_{own}} [\min (V_j(m_{own}) - V_j(m_2), 0)] \quad (28)$$

The disutility associated with ownership, $LCC_{m_{own},i}$, is determined externally based on vehicle specific costs and management time, and must be translated to a common time period

as $B_{m_{own},i}$. Allowing the consumer to have some preference between the two components, the final utility of owning mode m_{own} becomes:

$$V_{m_{own},i} = b_i B_{m_{own},i} - LCC_{m_{own},i} \quad (29)$$

The choice of ownership occurs when the benefits outweigh the costs. This is also defined as the requirement of $V_{m_{own},i}$ positive for aircraft owners, which means that the utility of ownership is greater than the utility of non-ownership where $B_{m_{own},i}$ and $LCC_{m_{own},i}$ are both zero by definition. This model is used deterministically, that is $V_{m_{own},i}$ must be positive.

In this case, the owner is the primary user of the aircraft, which calls for the use of a utility based ownership model, described in section 5.2.2. This model is only used to assess ownership of GAP aircraft, as the large majority of the GAJ fleet does not fall into the non-corporate category. After initial attempts at calibrating the model, it was seen that the number of aircraft in the non-corporate fleet could not be explained through measurable utility. Two modifications were implemented to account for these discrepancies: an aviation enthusiast model and a fractional ownership model. Fractional ownership is implemented in a simple probabilistic fashion: a prescribed fraction of owners see the acquisition price of the aircraft reduced by dividing by the number of owners.

Aviation Enthusiasts

The aviation enthusiast model is implemented to account for the fact that the size of the non-corporate fleet is not explained by the measurable utility alone. It is assumed that with the small population of pilots today, a large number of them engage in GA activity with a level of enthusiasm that decreases the importance of cost. In a hypothetical future where the number of pilots increases dramatically due to easy-to-fly technologies, we might expect the enthusiasts to be drowned out by more utilitarian, cost oriented users. A logical model is created to estimate this effect, which will moderate the growth of aircraft owners. The first big assumption made is that the number of enthusiasts in the entire population is limited, and that limit will be reached asymptotically as licensing increases. This can be approximated by a limited growth function:

$$N_{ent} = N_{ent,max} \left(1 - e^{-b \cdot lic}\right) \quad (30)$$

N_{ent} and $N_{ent,max}$ indicate the number of enthusiast pilots under any given licensing condition and the theoretical maximum, respectively. lic is the fraction of licensed households, and b controls the rate at which the growth reaches the peak value. N_{ent} , combined with the number of utilitarian, or normal, pilots, is equivalent to the total number of households, HH , times the fraction of licensed pilots. The fraction of enthusiast pilots in the pilot pool is:

$$f_{ent} = \frac{N_{ent,max}}{HH} \frac{(1 - e^{-b \cdot lic})}{lic} \quad (31)$$

This fraction is used in the analysis to determine if a licensed agent is labeled as an enthusiast. b was solved under the assumption that the current pilot pool consists of 75% enthusiast and 25% utilitarian, and that the theoretical maximum number of enthusiast pilots is twice that of today. As for ownership criteria, a utilitarian agent must see a positive annual utility of ownership, whereas an enthusiast agent is allowed a threshold extending into the negative range.

Finally, the utility based ownership model is implemented, and calibrated. Year 1995 data is used as the calibration point, to correspond to the *Mi* statistical databases. Results are verified against data from 1994 to 2005. To simulate each of these years, the reference aircraft price was changed in *Mi* to be consistent with the historical ratio of reference aircraft price (Cessna 172) to the 75th percentile income. The resulting number of agent owners for GAP aircraft is displayed for this verification process in Figure 49.

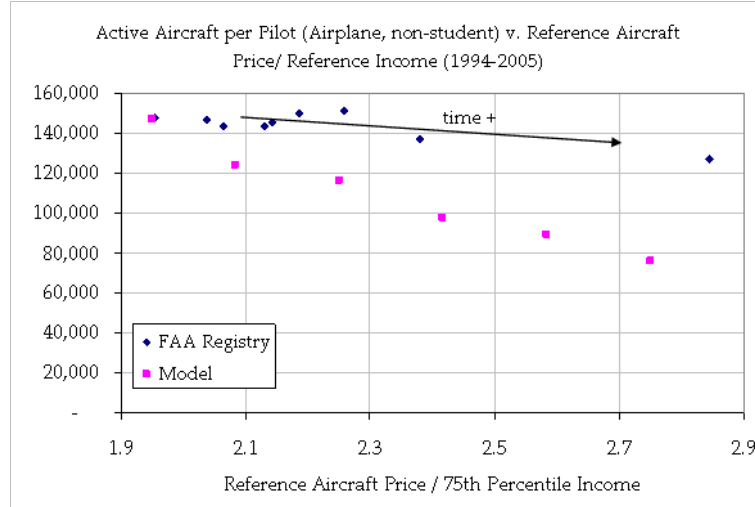


Figure 49: GAP non-corporate ownership verification results.

These results show a discrepancy from the FAA registry as the model moves away from the baseline. Actually, the model prediction is not time based, so each point represents a “ground up” estimation, where each simulated agent makes a decision based upon the current aircraft price. In reality, the consumers purchase an aircraft, and retain that aircraft for some time - they do not make a decision at each year. Thus, as expected, the model indicates much greater impacts as the price of the aircraft increases.

5.2.3 Rental and Charter

Proprietors of charter and rental services will procure a fleet of aircraft of a given size dependent upon the viability of operation. The formulation for assessing the scheduling, expenditures and receipts, and viability of such an operation is described, along with calibration in Chapter 6.

5.3 Demand Distribution

The *Mi* demand model as described in Lewe (2005) is not spatially or temporally explicit, meaning that the origin, destination, and time of travel are not specified. For the service providers, each local operation will likely need to be self-sustaining, hence requiring that the predicted demand be spatially distributed to fairly analyze the scheduling feasibility

and economic viability. Additionally, travel demand can fluctuate from week to week, which may significantly affect the scheduling of aircraft. Some weeks may see little utilization, while other weeks may see a lack of aircraft availability due to high demand; thus an effort to temporally distribute demand throughout the annual simulation is also sought. Spatial demand distribution is modeled through the adaptation of concurrent research methods of Lim (2008) and Yang et al. (2008), as well as implementation of spatial clustering methods. The temporal demand distribution is modeled directly according to decomposition of historical travel data.

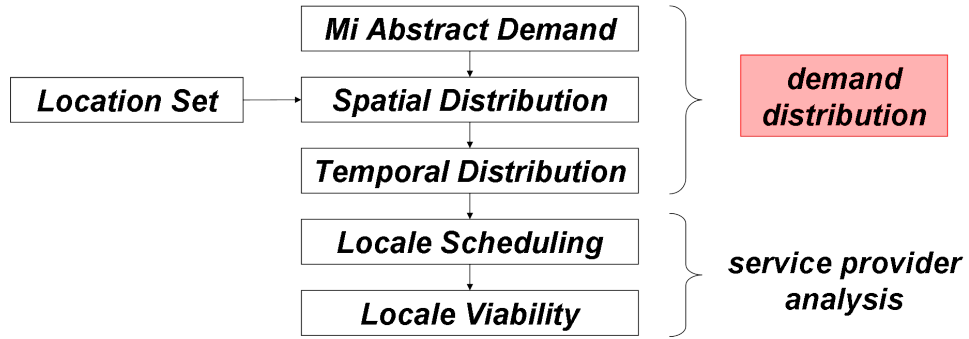


Figure 50: Flow of demand operations from *Mi* through service provider.

5.3.1 Location Set Definition

In an ideal situation, spatially explicit granularity is implemented as a part of the travel demand prediction model. In the current *Mi* model, spatial granularity is abstracted into four locale types: large, medium, small, and non-metro. The first three locale types are aggregations, by population bracket, of metropolitan statistical areas (MSA)³. Non-metro includes the aggregate demand at all other locations. This form of granularity was implemented within the holistic perspective of the model's development, and it is a means to streamline the analysis capability by eliminating problems associated with increasing granularity, thus allowing the user a high level and more manageable environment.

The service provider envisioned within this thesis is a group of mostly independent service provider operations, spatially distributed to explicit locales across the US. This assumption

³Current definitions can be found at <http://www.whitehouse.gov/omb/inforeg/statpolicy.html> (acc. 05/2008)

means that the aggregate demand must be fairly distributed to a set of locales. As a starting point, the highest level of granularity is set forth: 157 MSA locales, representing 180M people, and 2,607 non-metro counties, representing the remaining 85M people. The set of MSA locales are in a form that is sufficient for direct use; each population is large enough and spatially compact enough to be considered as serviced by a single service provider. The non-metro counties need to be further manipulated to create a fair and balanced implementation.

A proper balance will address two concerns. The first concern is implementing a proper granularity. A sufficient granularity accounts for a balance: high enough such that a service provider location does not see an artificially high demand due to over aggregation, and a logical amount of aggregation, such that populations which are nearby to one another can be considered as providing demand to a single service provider operation, maximizing their potential for success. The second concern addresses the computational aspects, namely the isolation and elimination of very small populations such that the number of discrete populations is manageable, while at the same time capturing a large enough portion of the total population.

Clustering methods are sought to address the aforementioned concerns in the locale set selection process. Clustering is a means of partitioning a set of spatially defined data into a small group of memberships, or clusters, which share common properties. In this case, the property under consideration is the spatial location on the US map. The purpose of a clustering algorithm is to determine cluster centers, which for this analysis is the origin from which all populations within a specified radius, are considered as belonging to a common cluster. A generalized method for the clustering of populations is displayed in Figure 51.

The locale selection process begins with the clustering algorithm. After implementation of the clustering algorithm, the potential cluster centers are tested for two criteria. The first criteria is that the maximum distance from any county to the cluster center is less than a specified distance, d_{max} . This value can be considered as the greatest distance for which a user might travel to use the service, and should correspond to the value used in determining the portal access time. The second criteria, which is only necessary to be implemented when a reduction in the population is desired for computational purposes, is the minimum

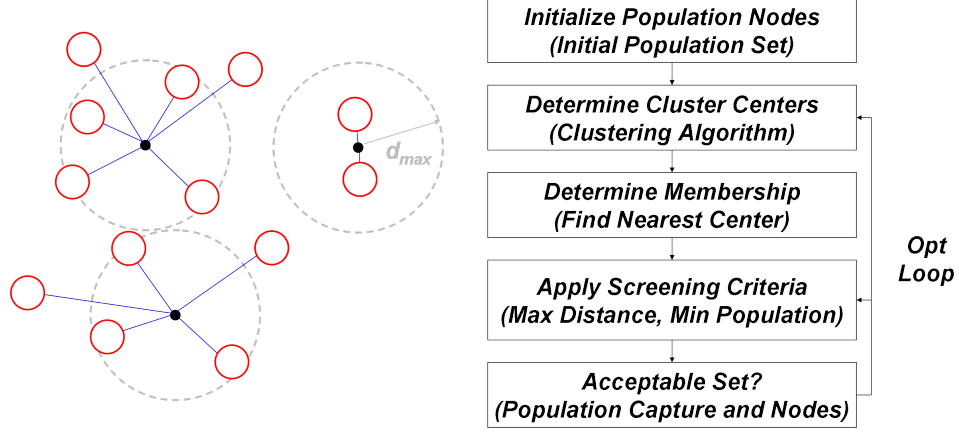


Figure 51: General clustering method for determination of SP locales.

population criteria. In this step, all clusters, and all individual counties which have been excluded membership in a cluster due to the distance criteria, are truncated if their total population is less than Pop_{min} . The final result is a set of discrete populations (individuals and clusters), or nodes, which capture a portion of the original population. If a sufficient portion of the original population is not captured, or the number of nodes is too large, the minimum population criteria can be varied until a proper balance is achieved.

Two common clustering algorithms are tested: subtractive (SC) and fuzzy c-means (FCM) (see Hammouda (2004) for a concise overview). Additionally, a simple algorithm is implemented as a baseline for comparison. This algorithm, dubbed largest populations (LP), assigns all counties with population greater than a critical population, Pop^* as a cluster center. Each of these algorithms has a single, unique clustering parameter which can be adjusted and optimized. The parameters are radius of influence, the number of potential cluster centers, or seeds, and Pop^* for SC, FCM, and LP algorithms, respectively. The SC and LP algorithms automatically determine the number of seeds based upon each populations measure of its clustering effectiveness. Thus, in these methods, cluster centers coincide with existing populations. On the other hand, FCM attempts to optimally distribute a specified number of seeds, and the cluster centers can reside at any point in the space. This aspect means that clustering will in most cases be more efficient, except for special cases where the optimal cluster centers are existing populations. In return, FCM is more computationally expensive.

The parameters for the respective algorithms are optimized. Specifically, the parameter setting which results in a minimum number of nodes is sought. First, d_{max} and Pop_{min} must be set. Pop_{min} does not affect the parameter optimization, because as it is increased, nodes will be systematically eliminated from smallest to largest regardless of the determination of the cluster centers. d_{max} does affect the parameter optimization, and hence a reasonable value of 25 miles is chosen. At this point, the determination of this value is subjective, as location specific details must be known for numerical optimization. Since the optimization problem is of a single dimension, a grid search is sufficient. The results are displayed in Figures 52 through 54.

Under all algorithms, a parameter value of zero, indicates no clustering, and the original 2,607 counties are represented. In all cases, the entire population is captured, as Pop_{min} has been set to zero, meaning that no populations are discarded. Additionally, the number of nodes indicates the total number of individual counties and county clusters. While the simple LP algorithm performs poorly, it shows that any amount of clustering can significantly reduce the number of nodes one needs to handle, assuming that the d_{max} criteria is acceptable. The FCM method is clearly shown to be the best choice for this problem, reducing the number of population nodes to almost half of the original value.

Next, the optimal clustering parameters are held constant, and the population criteria, Pop_{min} , is increased. As Pop_{min} increases, population nodes of insufficient size are discarded, which reduces the number of population nodes, but also the fraction of total population captured, i.e. the total number of people. The selection of Pop_{min} is thus a multi-objective problem, trading the population captured, which ideally should be maximized, and the number of remaining nodes, whose minimization is desired for computational and manageability purposes.

The final value is chosen *a priori* to the analysis, although some levels of acceptability are first set forth. For sufficient viability, a locale requires on the order of 100k people. Under nominal conditions, a population of this size would contain approximately 250 pilots on average. Under aggressive assumptions, this could result in as many as 2,500 pilots per locale. Air taxi users may potentially double that value. This base of potential users, only a

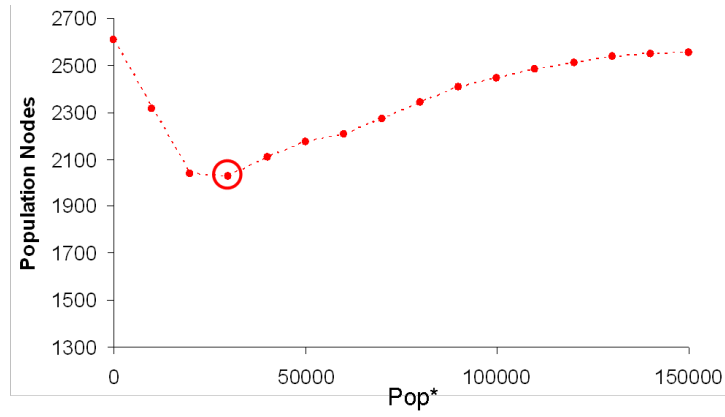


Figure 52: Optimization of LP clustering parameter (Pop^*).

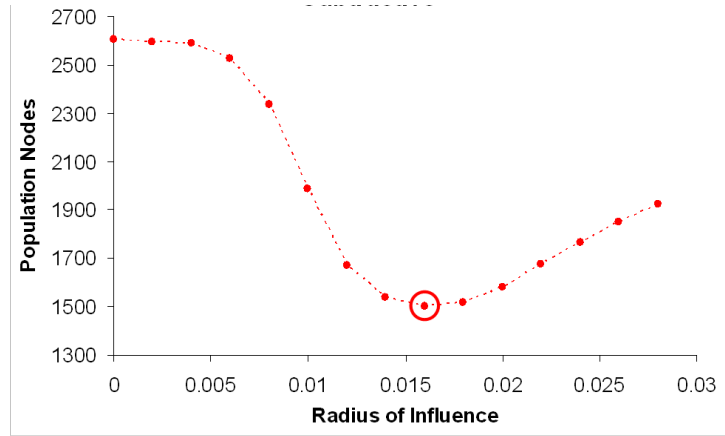


Figure 53: Optimization of SC clustering parameter (radius of influence).

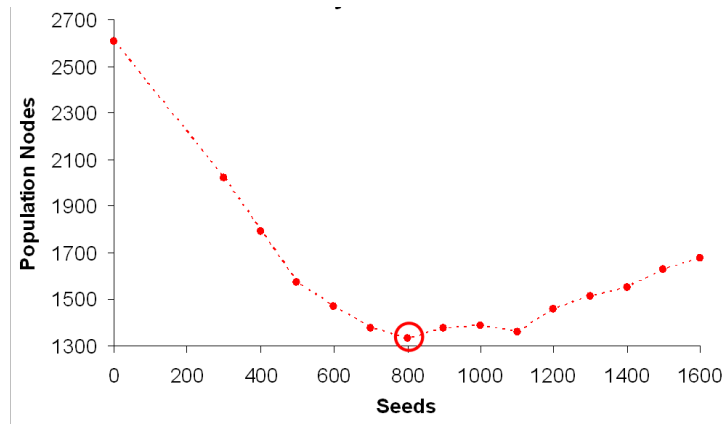


Figure 54: Optimization of FCM clustering parameter (seeds).

fraction who may decide to use the service on occasion, is likely sufficient. For computational purposes, the total number of nodes, including MSA locales, will begin to cause exceedingly large computational time above a value of around 500.

The number of nodes and the population captured under parametric variation of Pop_{min} from zero to 150k are displayed in Figure 55, including all clustering methods, as well as no clustering (NONE). Recall that the original population consists of 85M people and 2,607 individual county nodes. The direction of increasing Pop_{min} is indicated by the arrow, the ideal solution is the top left corner, and the final selection is indicated by the red cross hairs, which corresponds to $Pop_{min} = 100k$.

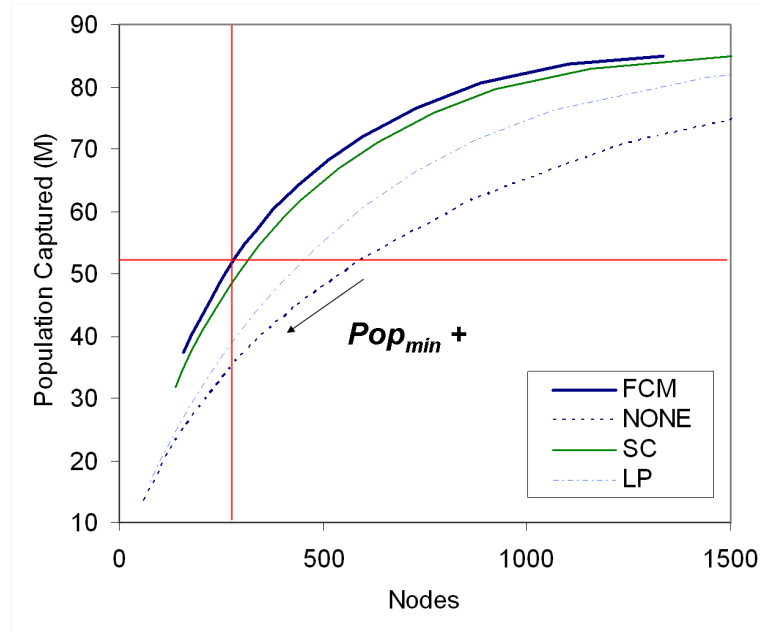


Figure 55: Tradeoff frontier for minimum population criteria.

The FCM algorithm clearly dominates all others, although SC is considerably close. Because the determination of locales is performed off-line, the issue of computational time is not critical and thus the FCM results are the clear choice. Otherwise, SC would likely provide a suitable alternative. The selected results capture 52M people, or about 60% of the original population, and consists of 282 population nodes. For comparison, without clustering, the same number of nodes can optimally capture 37M people (follow cross-hairs down), and the

capture of the same population would require 593 nodes (follow cross hairs right). Additionally, geographical mapping of the results shows that clustering not only allows reduced computational burden, but also more fairly represents potential service provider locations, as seen in Figure 56 (Note: MSAs are excluded from plot). Here, the population nodes are mapped for a select portion of the US, with the optimal clustering set displayed in the center, and, without clustering, the remaining population nodes for equivalent number of nodes (left) and equivalent population capture (right). This clearly shows that nearby populations can share a common service provider location, and in the process boost their potential for viability through increase demand volume.

5.3.2 Spatial Distribution

With a set of locales determined, a basis is set for the distribution of the travel demand predicted by M_i , to each locale. The next step is to determine the proportion of demand that is to be allotted to each locale. Originally, this was performed by simply proportioning the demand at each locale by the locale's population. Recent efforts by Lim (2008) and Yang et al. (2008) allow a more detailed approach. Together, these methods have helped to formulate an origin-destination matrix (O/D) between all locales based upon a corrected gravity model, which accounts for several socioeconomic factors (e.g. mean income, entertainment and dining revenues). Each element of an O/D matrix indicates the volume of travel between each origin (row) and destination (column) pair.

The process of using this generated O/D matrix, OD_{jk} , is depicted in Figure 57, where the process starts with the abstract demand vector, D^d , for which the elements are trip demand for each distance bracket, $d \in \{100, 150, \dots, 2800\}$, and the final product is a spatially explicit demand vector, D_i^d , for each location $i \in O$. The required intermediate step is to decompose the original O/D matrix into a set of matrices, OD_{jk}^d , each including only the trips for the specified distance bracket. This is done by calculating the distance between each O/D pair, using the known coordinates of the county or cluster center. Each of these matrices is then normalized and multiplied by the corresponding abstract demand, which gives the O/D matrix, D_{jk}^d , simulating the distribution of the predicted demand.

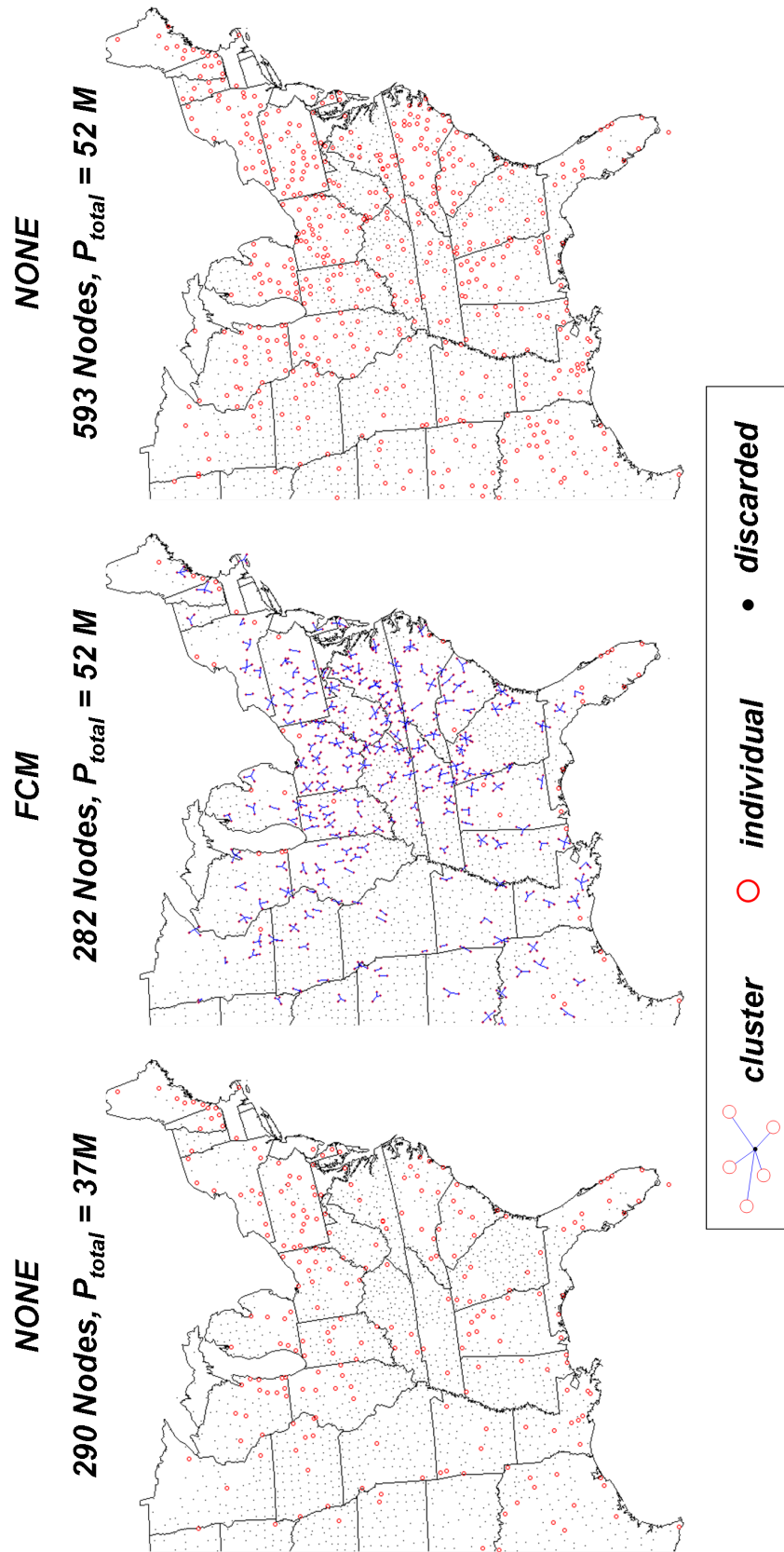


Figure 56: Optimized clustering (center) vs. equivalent unclustered sets (MSAs excluded).

Finally, the demand at each location is found by summing along the rows of each matrix.

5.3.3 Temporal Distribution

The goal of the temporal distribution model is to spread the aggregate demand across the simulated time period. Demand characteristics vary temporally based on the time of the year, e.g. summer and holiday peaks, and on the day of the week. Additionally, the length of stay for every trip varies. These variations in demand will affect the ability of a service provider to schedule the demand, and ultimately determine the fleet size that best balances the loss of demand during peak periods with the costs of under-utilized aircraft in the non-peak periods.

Development of the model is driven by a study of historical traveler and travel demand characteristics, with emphasis on creating a stochastic model to account for consumer to consumer and trip to trip variation from the norm. The output of the temporal distribution model is a day by day calendar of potential departures and arrivals at each service provider locale. There are three sub-models which compose the temporal distribution model and answer the three questions: what week of the year does the trip begin, is this a weekend trips, and how long is the stay?

The first sub-model determines the week of the year that a given trip begins. The modeling data comes from the monthly Bureau of Transportation (BTS) T-100 domestic segment enplanement data from 2005 to 2007⁴. This data counts the number of passenger enplanements each month, as reported by the airlines. Although the number of enplanements is larger than the number of passenger-trips, due to connecting flights, the information sought for this model is the relative distribution of trips across the year, and not the magnitude. Thus, normalizing the monthly enplanement data by the total annual data should provide the necessary information, if the assumption that the volume of demand does not significantly affect the ratio of enplanements to passenger-trips⁵. The T-100 data is summarized by the graph in Figure 58, where the contributions of all months sum to one. Also included in

⁴The most recent data can be downloaded from <http://www.bts.gov> (acc. 06/2008).

⁵In this context, an enplanement signifies a passenger boarding an aircraft, whereas a passenger-trip signifies a traveler moving from their origin to final destination.

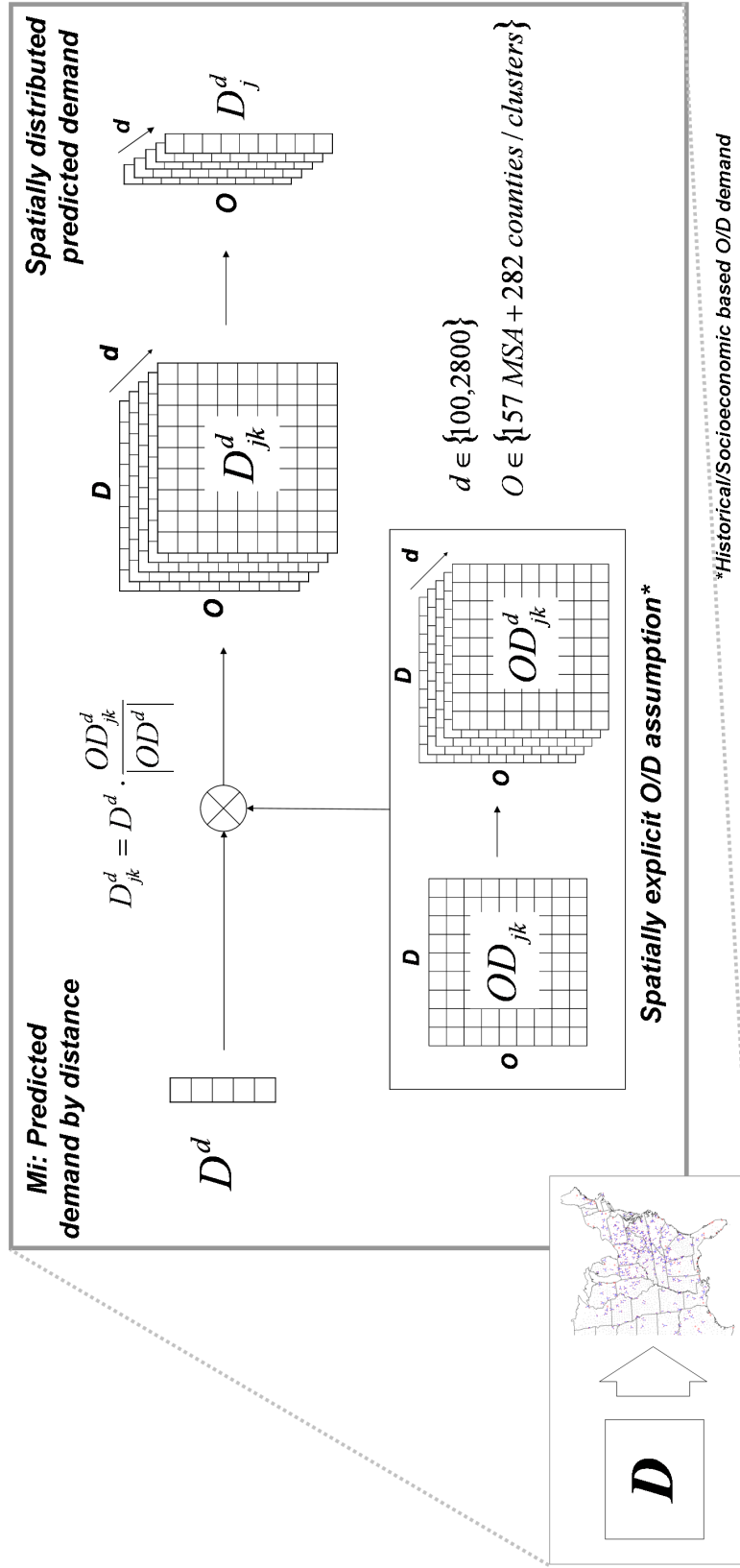


Figure 57: Depiction of abstract to spatially explicit demand distribution.

this chart is a measure of automobile highway traffic distribution, summarized in Festin (1996), as counted by 5,000 automated traffic recording devices across the US. This possible alternative is not used in the model, as all traffic is counted, with the inclusion of daily commuter traffic.

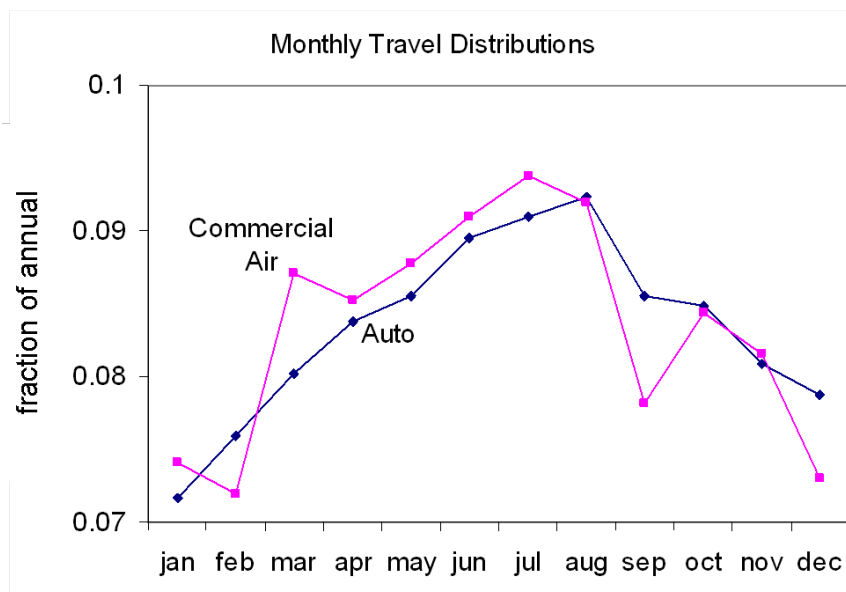


Figure 58: Historical distribution of travel by month.

The commercial air enplanement distribution shows that travel is heaviest in the summer months, and lowest in the winter months. This is mostly expected, except for a lack of the “holiday spikes” which are expected in the months of November and December. Because this data is monthly, the extreme lack of travel at other weeks within those months seems to be drowning out these expected anomalies. These factors should be taken into account in adjusting the final model.

For modeling purposes, some liberties are taken into translating the monthly travel data into a weekly demand probability distribution. The primary assumption taken here is that the probability that a given trip occurs on any given week is proportional to the measured travel volume of that week. The monthly travel data is converted into weekly data by linear interpolation between monthly data points, assumed to be in the middle of each month, and renormalized such that the total of all weeks sums to one. The missing “holiday spike” is also

added by increasing the relative demand in the last two weeks of the year, and decreasing it in the first two weeks. This final distribution is now used as the probability distribution function for determining the departure week of each trip, i.e. the week of departure is found by randomly selecting a value among the discrete set $w \in [1, 2, \dots, 52]$, where each value has the probability, $p(w)$, of being selected.

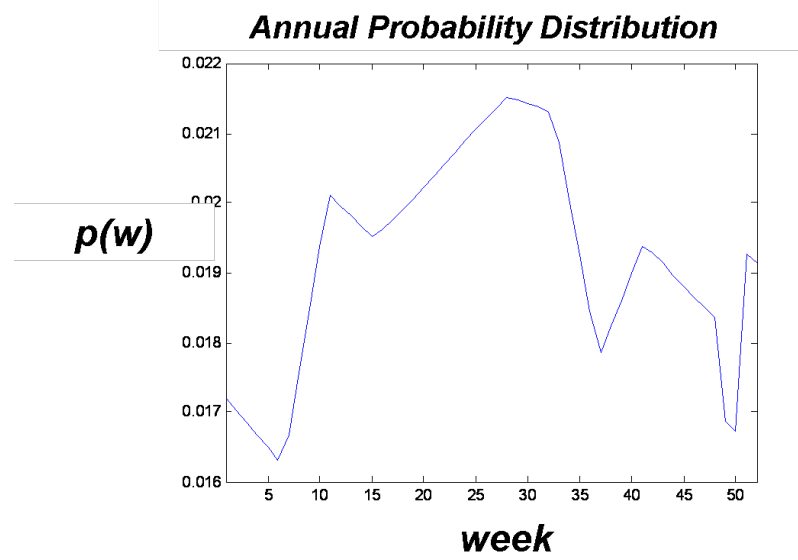


Figure 59: Weekly demand distribution model.

The second and third sub-models are based on a survey of 80,000 travelers, of which a brief summary can be found in BTS (1997). The data utilized from these surveys are for those trips specifically noted as using GA as the primary mode. The second sub-model determines whether a trip is considered as a “weekend” trip. This definition limits the length of stay from one to five days, and requires that a Friday or Saturday night be included. The determination of this characteristic is assumed to only be a factor of the trip purpose. The summation of weekend and non-weekend trips for each of these trips from the original survey database results in the distribution found in Table 23. The model probability that a given trip, with known purpose, has the weekend characteristic is assumed proportional to these surveyed values.

Table 23: Probability for assignment of “weekend trip” characteristic.

Weekend?	Personal	Business
Y	46%	11%
N	54%	89%

The third sub-model is used to assess the length of stay, measured by the number of nights away. Study of the survey data finds that the average length of stay for a given travel distance can be approximated, also given the trip purpose and weekend characteristic. These trends are displayed in Figures 60 and 61.

These trends form the backbone of the sub-model, but clearly some distribution around these average values must be accounted for. Closer inspection of the data set, indicates that in most cases, the mean and mode value stay length for a given distance tend to coincide⁶, as seen in Figures 62 and 63. The only exception is that for non-weekend business trips, for which the mode is zero, regardless of the distance traveled.

These distribution characteristics can be captured by a beta distribution, which is defined by two shape parameters. For non-weekend business trips, the distribution is defined such that the mode is zero, and the mean follows the corresponding trendline in Figure 63. The remaining three trip types have approximately the same mean and mode, which only occurs for a special case. The sample data set is too small to accurately and consistently provide the variance around the mean value, although the data showed that the variance tends to increase as the distance traveled increases. For the remaining models, the beta distribution is given an alpha shape function of five, and the mean is given by the mean value trend lines, as plotted in Figures 62 and 63.

Examples of the probability density function used for random selection the stay length, n , of a given trip, for a few selected distances are shown in Figures 64 and 65. Notice that in the case of the personal, non-weekend model, the peak follows the mean trend line of Figure 62, and in the case of the non-weekend business model, the mode remains zero, while the mean also follows its corresponding trend line.

⁶Note that the number of sampled travelers in the survey using GA is relatively small, resulting in a significant amount of noise between the mean and mode values.

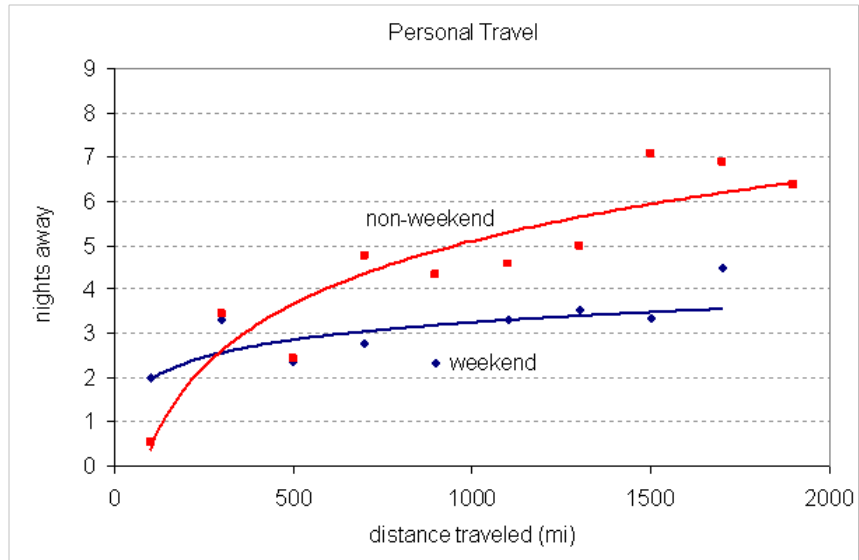


Figure 60: ATS personal travel characteristics.

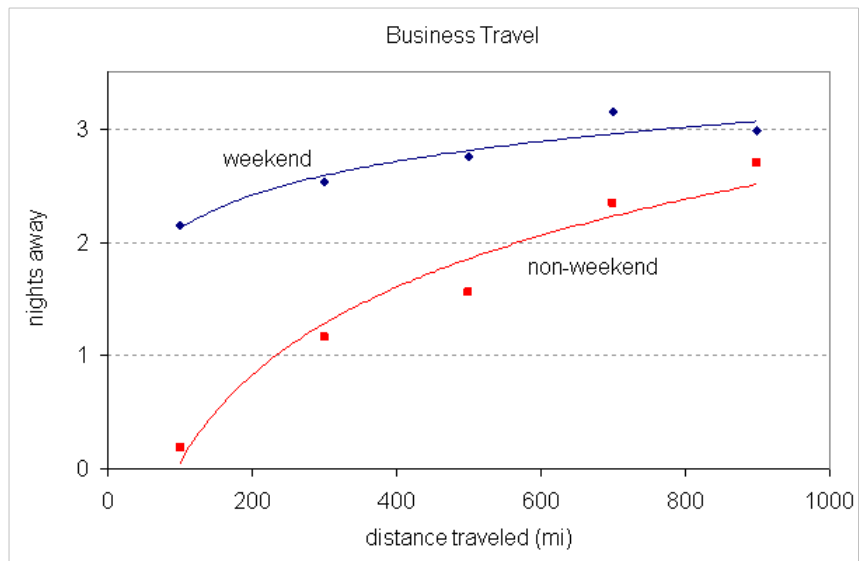


Figure 61: ATS business travel characteristics.

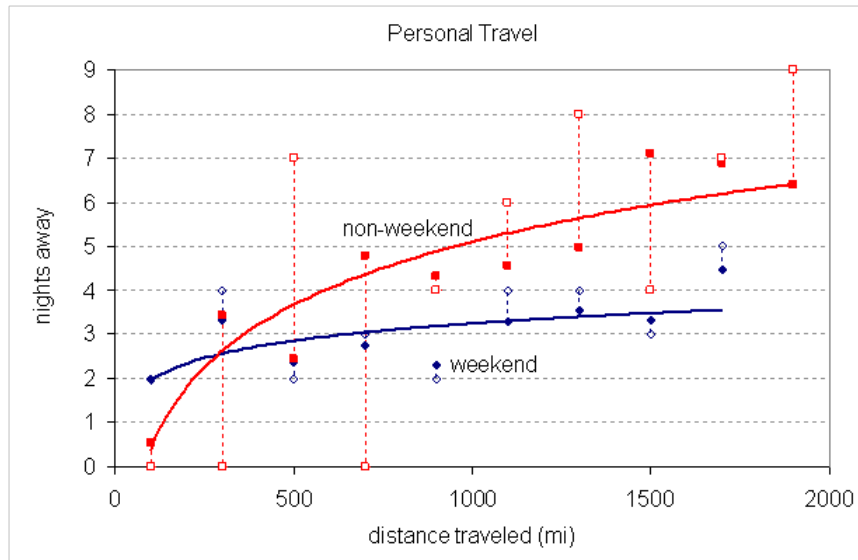


Figure 62: ATS personal travel characteristics (● - mean, ○ - mode).

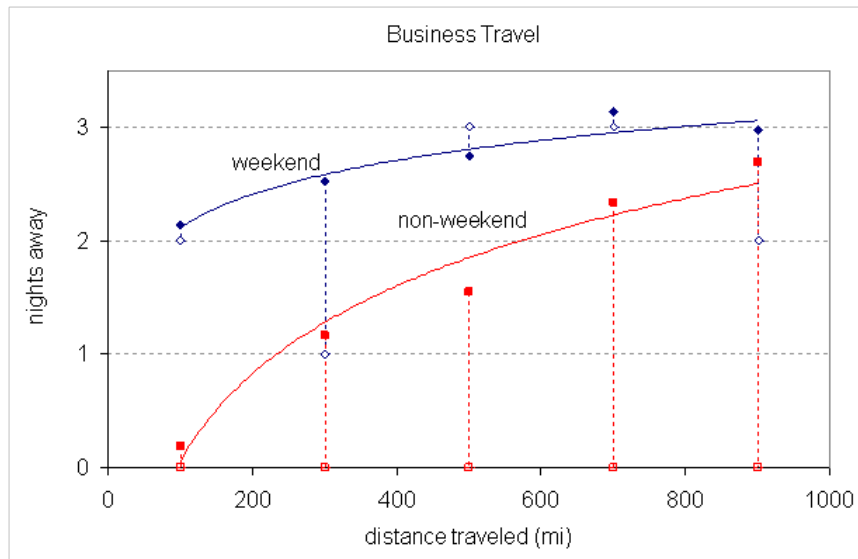


Figure 63: ATS business travel characteristics. (● - mean, ○ - mode).

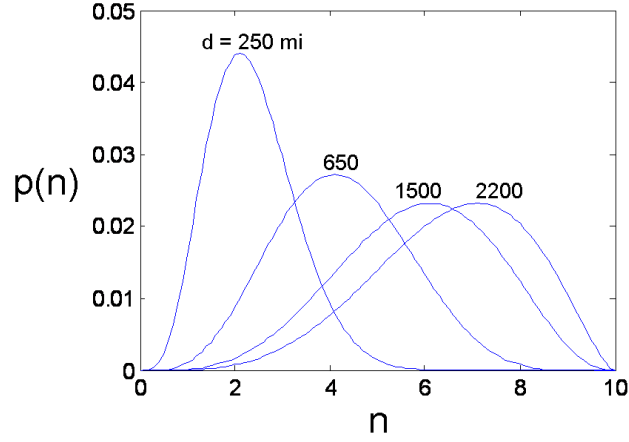


Figure 64: Personal, non-weekend stay length model.

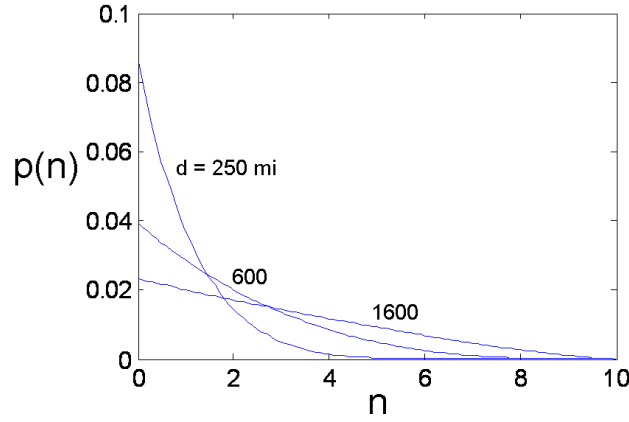


Figure 65: Business, non-weekend stay length model.

The three sub-models indicate the week of departure, the weekend trip characteristic, and the stay length. This information is combined with a set of departure day rules to build the final agenda. Given the departure week, the departure day rules simply take the weekend characteristic and the stay length, and enforce the weekend and non-weekend definition. Departures can then be randomly selected among the allowable days, with uniform probability of selection, to determine the actual departure date. The departure day rule set is depicted in Figure 66.

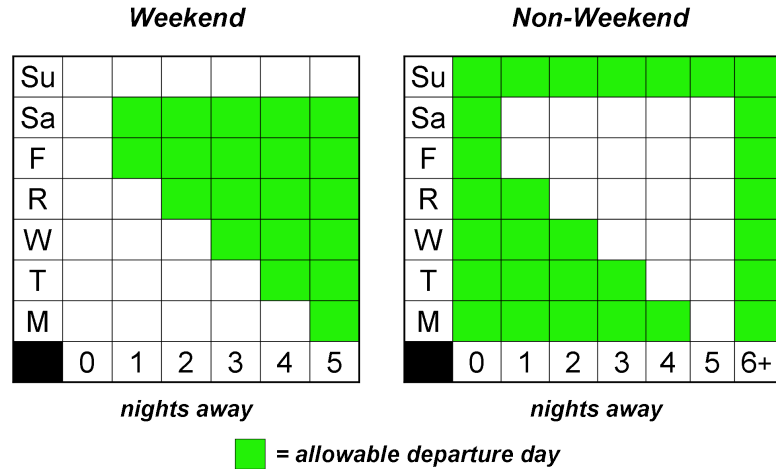


Figure 66: Departure day rules.

Each trip, all of known distance and purpose, at a service provider locale is subjected to the preceding temporal distribution model, endowing the trip with departure and return dates. Once all trips are assigned these dates, they are ordered by departure date, and a demand calendar is built for that locale. The overall process is summarized in Figure 67, where in the depicted demand calendar, each trip is represented on its own row, and the blue area indicates when it is active. This calendar is now ready to be put through the task of scheduling by the service provider.

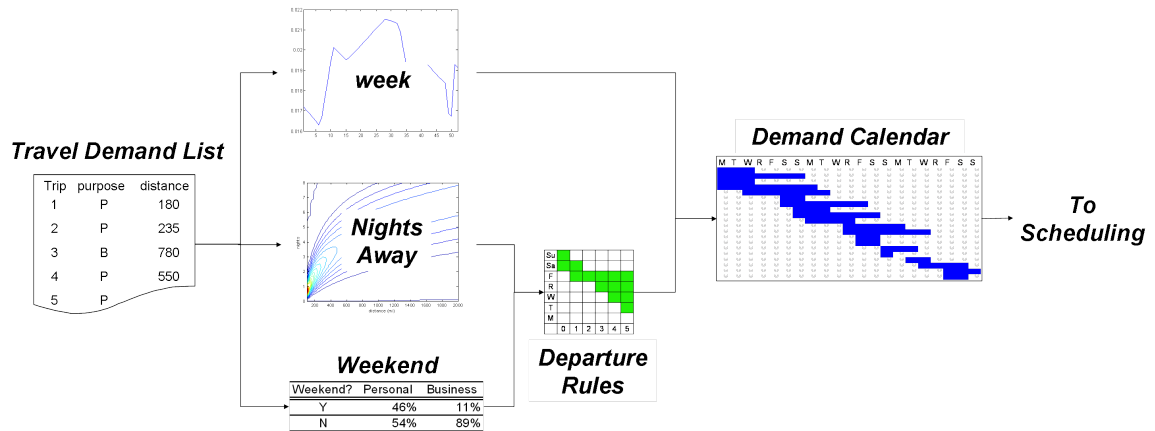


Figure 67: Overview of temporal demand distribution model.

Chapter VI

SERVICE PROVIDER MODELING

The service provider (SP) brings the GA mode to consumers without the burdens of ownership. In return, the consumer pays for the service, supporting the viability of the service. The service provider faces decisions concerning the selection of aircraft attributes, the size of their fleet, and the economics of operation in hopes to maximize the scheduling of demand while attaining an acceptable profit.

The service provider analysis is thus composed of trip scheduling and economics. The trip scheduling algorithm must capture any disparity between user demand and the aircraft availability, such that demand is feasibly captured. The economics component must capture any disparity between the receipts and expenses of operation, and provide a metric by which each simulated service provider can make a “go or no-go” decision.

6.1 GAP Service Providers

For GAP aircraft, the service provider methodology explained in this section is used to ultimately determine the viability of operation at a set of locales. The operation, in general, acts like that of a current day aircraft rental operation, but can be modified to act more like a car rental agency, which may be desired in the analysis of revolutionary concepts. The former operation typically caters to enthusiasts willing to fly in aged aircraft and bend their schedules to meet the availability of the aircraft with little to no customer service. The latter operation, which is practically non-existent today, is more customer driven, requiring newer vehicles, a high level of availability, and good customer service. Either operation can also explore the option of making chartered flights available to those without piloting ability, by adding a charter fee.

As described in the previous chapter, and depicted again in Figure 68, the abstract demand predicted by M_i is distributed spatially to a set of locales. The locales are determined

through a clustering procedure, and the demand - a list of trips identified by trip distance and purpose - is distributed to the locales based upon an aggregation of socioeconomic metrics and the distance to potential destinations. The trips are then distributed temporally, resulting in an annual agenda of demand. The purpose of the service provider model is to determine the scheduling of those trips, based upon the availability of their fleet, and if the local operation is viable.

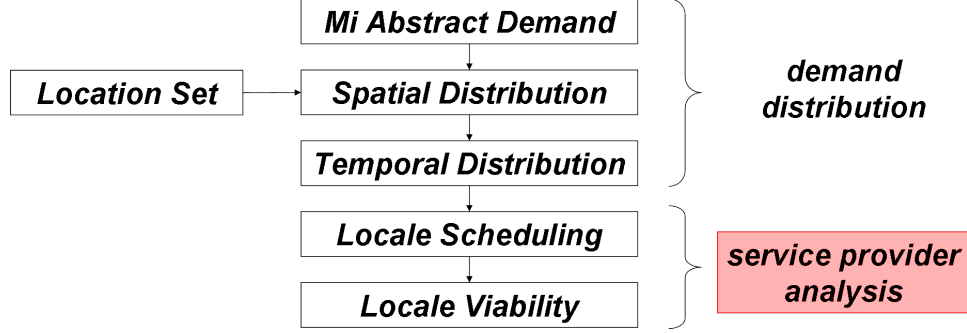


Figure 68: Flow of demand operations from *Mi* through service provider.

6.1.1 Scheduling

Demand scheduling concerns systematically comparing the customer demand with the availability of aircraft. If plenty of aircraft are available, all customer demands will be met, but higher costs will be incurred to acquire and maintain the fleet. On the other hand, a small fleet to demand ratio may allow a viable operation for the service provider, such as in the case of current day flying clubs, but require that the customer bend their schedules to the aircraft availability or choose not to use the service. Thus, a primary variable, fleet loading, is defined:

$$fl = \frac{D_{j,avg}}{Q_j} \quad (32)$$

Where Q_j is the size of the fleet, and $D_{j,avg}$ is the average weekly expected demand, in trips, both at service provider location j . If the service provider chooses a high fleet loading value, they are forcing more demand to be allotted to any given aircraft in the fleet, lowering the acquisition cost of the fleet, yet increasing the possibility of losing demand. A low fleet

loading value means that each aircraft is allotted a small portion of the average demand, increasing the cost of the fleet, yet assuring more demand is feasibly captured.

In the previous section, the demand calendar, or agenda, that is the day by day calendar of demanded trips was created. With the fleet size known, this demand is now attempted to be scheduled. In some cases, all the demand is captured, but in general some will be lost due to the lack of available aircraft. The algorithm for the scheduling process is displayed in Figure 69.

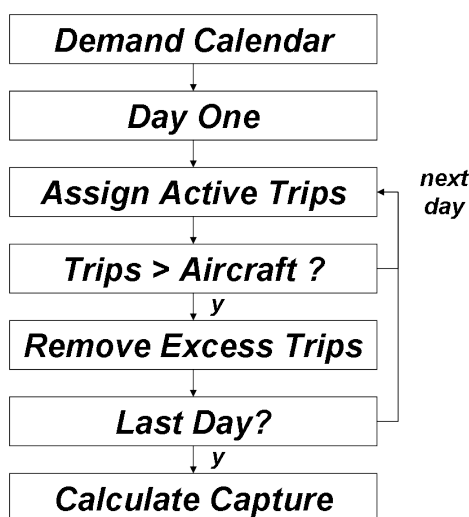


Figure 69: Demand scheduling algorithm.

In short, starting from the first day of the year, the number of trips demanded is compared to the number of aircraft available (an aircraft is not available when it is assigned to a trip during its active time period). If there are not enough aircraft, the appropriate trips are considered as lost and struck from the calendar. This procedure is repeated until the last day of the year. Trips that are scheduled are counted as captured, trips that are not scheduled are counted as lost, and the capture fraction, F_c , is the ratio of captured trips to all demanded trips.

A sample of results is displayed in Figure 70. In this sample, a notional demand was calculated, spatially distributed to 439 locales, as described in the previous section, temporally distributed, and scheduled. The average capture fraction (AVG), as a function of fleet loading, is plotted as an average across all locales, and also for two select locales with

annual demand, D , in trips as indicated.

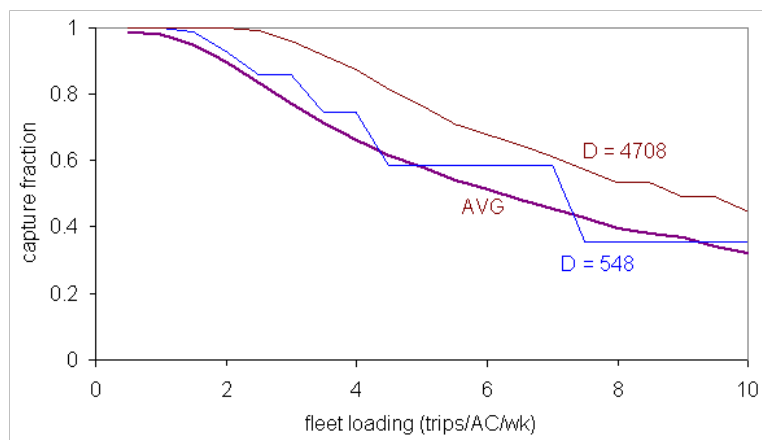


Figure 70: Demand scheduling sample results.

There are noticeable differences in the trends for the individual locales, namely that the locale with small demand tends to schedule less demand, and is also very jagged. The jagged nature arises as the smaller locale has only a few aircraft, and since only integer values of aircraft are allowed, the loss of an aircraft as fleet loading increases results in a larger chunk of lost demand. The locale with larger demand has a significantly larger number of aircraft for a given fleet loading value, and hence the loss of an aircraft is less noticeable. This also makes the locale less susceptible to demand variation, as indicated by the greater capture fractions.

6.1.2 Economics and Viability

A service provider model must have a realistic set of calculable expenses and receipts, as well as a method for translating them to a measure of viability for the “go or no-go” decision. First, the set of expenses and receipts will be presented, some of which have been parametrized to aircraft specific inputs, and then the methods for determining viability will be briefly explained. All dollar values are 2007 unless otherwise noted.

To begin, there are few texts for this subject, and for the most part trends will change from business to business. Conklin and Decker (1998) explain the costs associated with aircraft fleet ownership. In addition, Carroll (2007), treasurer of the Yellow Jacket Flying

Club, provided a summary of the expenses associated with their operation. Plane and Pilot Magazine also provides a source of practical GA ownership information (e.g. see the article by Smith (2006a)). Finally, AOPA (2008) provides an online calculator for expected ownership costs. From these sources, a summary of the expenses and receipts is developed, divided into fixed costs and variable, or direct operating costs.

Table 24: List of service provider expenses.

(a) fixed	(b) variable
Fixed (year)	Variable (hour)
Aircraft Finance	Fuel
Aircraft Insurance	Oil
Hangar/Tiedown	Inspection
Staff	Engine Overhaul
Land	Unscheduled Maint.
Income Tax	(Rental)
Property Tax	
(Depreciation)	

Aircraft Finance

The aircraft is assumed to be paid over the program length, N . This is the period of time from which the fleet is acquired, to the time at which it is relinquished for a residual value, $R(N) \cdot ACQ$, which is assumed to account for the final loan payment. For an interest rate, i , the yearly payment is as follows:

$$FIN = ACQ \frac{(1+i)^N - R(N)}{\sum_{n=0}^{N-1} (1+i)^n} = ACQ \frac{i((1+i)^N - R(N))}{(1+i)^N - 1} \quad (33)$$

Aircraft Property Tax

Every year property is taxed on the state level. Property tax laws for aircraft vary from state to state. A nominal value of 1.5% is used. The value which is taxed depends on the state method, but it will be assumed here that the tax value is the same as the current year residual value. Then, at year n , the property tax is simply $R(n) \cdot ACQ \cdot \text{property tax rate}$.

Aircraft Depreciation

The depreciation of the aircraft fleet can be deducted from the business's income for

tax purposes. The value of depreciation depends on local tax laws, but here it is assumed that the annual depreciation is the difference in residual value from the previous year to the current year, or $ACQ(R(n-1) - R(n))$.

Corporate Income Tax

The corporate income tax rate schedule for the year 2007 is implemented. Taxable income is the sum of all revenues less allowable expenditures and asset depreciation. All expenses considered in this analysis will be assumed as deductible expenditures, along with the calculated aircraft depreciation.

Residual Value

The residual value, $R(n) \cdot ACQ$, is that value the aircraft is worth a given number of years after purchase. This value determines the recovered cost of an aircraft after the program length as well as the price paid for an aircraft bought used. The relative residual value, $R(n)$, is the fraction of the original acquisition cost, ACQ , the aircraft is worth at year n . For the purposes of this study, the residual value will also be assumed as the tax value. Conklin and Decker (1998) provide a relative residual value schedule, in percentage of new value, for piston aircraft over a length of 30 years, after which time the value approaches zero, as seen in Figure 71.

It seems that piston aircraft retain a significantly greater value than predicted. To confirm this trend for GAP type aircraft, a survey of asking price - i.e. advertised sales price - was taken from several online sales sites¹. Also, the manufacturer retail price for new Cessna 172 aircraft, from 1996 to 2007, was investigated (P&P, 2000, 2003). Surprisingly, the price of a new Cessna 172 remained at approximately \$162,000 in 2007 dollars. To estimate the residual value, the asking price for the used aircraft is divided by the new price, and indexed to the known age of the aircraft. Results are displayed in Figure 71, along with an exponential approximation that is used in the current analysis.

¹Values found at http://www.pilotmarket.com/aircrafts/Aircraft_For_Sale/Single_Engine_Piston/Cessna/172/ and <http://www.aircraftdealer.com>, in 12/2007.

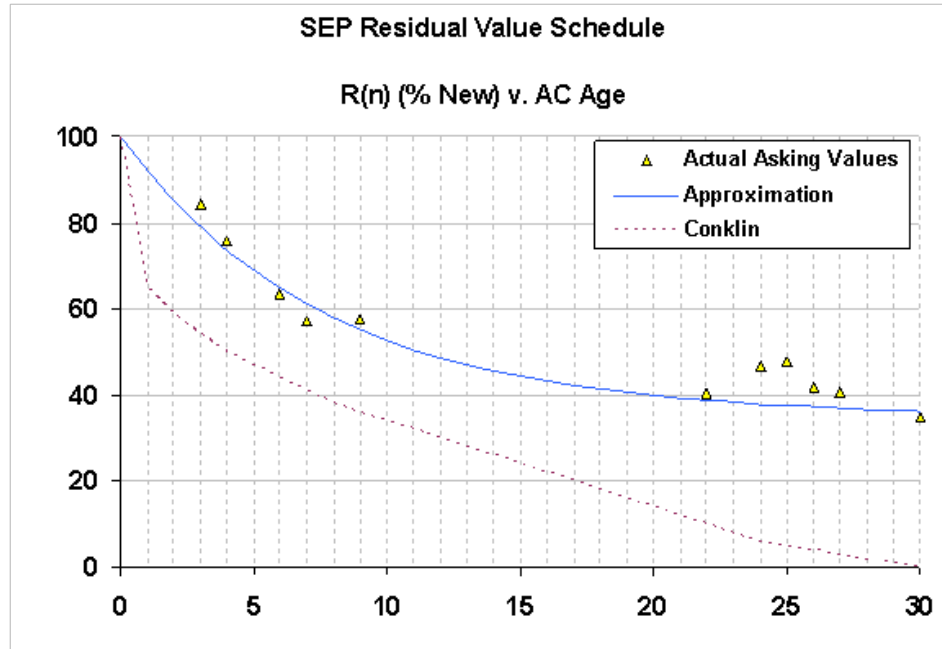


Figure 71: SEP residual schedule models.

In comparison to Conklin and Decker (1998), the residual value drops slower, and attains approximately 30% of its value after 30 years. Although an aircraft may not be sold for the listed asking price, one would assume it to remain with 80% of that value. From the early 1980's to mid 1990's, Cessna shut down many of its single engine piston production lines - often considered an effect of the “liability crisis” - resulting in the data gap between 10 and 20 years.

Aircraft Inspection

Annual inspection is superseded by the 100 hour inspection when applicable. For the service provider, it is most likely that the annual inspection will be unnecessary, as 100 hour inspections should be more frequent than one year. Otherwise the same cost as provided for 100 hour inspection will be used.

Insurance

A survey of insurance quotes for several SEP aircraft at their new values was taken. This provided a smooth curve to estimate the cost of insurance for SEP aircraft based on the insured value. The formula is given in Equation 34 and plotted along with the survey

values in Figure 72.

$$C_{insurance} = 1028.8 \cdot \exp(0.0037 \cdot \frac{ACQ}{1000}) \quad (34)$$

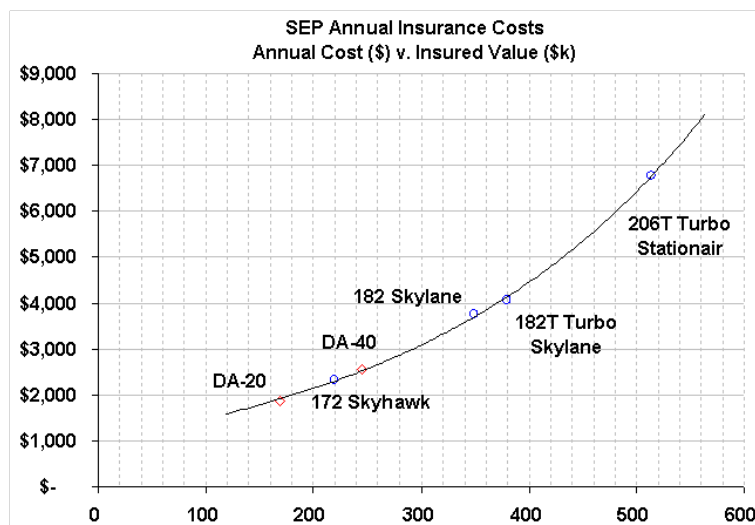


Figure 72: SEP insurance costs.

Land

The cost of land can be broken into the cost of office/customer accommodations and hangar or tie-down. On the order of \$10,000 per month is a reasonable estimate for office and customer accommodations. This is dependent on many considerations of the operation, including customer base (e.g. business jet charters have very nice accommodations), the location, etc. Hangar and tie-down costs are estimated by AOPA at \$10,000 and \$3,000, respectively, per aircraft per year.

Staff

Staff can include administrative, operations, and pilots. The administrative and operations is grown with the size of the aircraft fleet and demand. These employees also require an overhead factor to account for costs necessary to perform their job. Pilots for charter operations are assumed to be paid by each hour flown.

Fuel and Oil

Aircraft performance data will allow the ability to calculate the amount of fuel burnt

during a rental or charter period, which is translated to a total fuel cost given the cost per gallon of fuel. In practice, the fuel is typically paid for by the service provider.

According to AOPA, the cost of an oil change is approximately \$150 dollars per engine. An oil change is required by the FAA every 50 hours, translating to approximately \$3 per hour.

100 Hour Inspection

The inspection cost varies primarily by the complexity of the aircraft, namely the number of engine cylinders, and the type of landing gear. Table 25 shows the cost of inspection for a few configurations, as quoted by AOPA. Also shown is the typical SHP class for the number of cylinders. These values are used to create a discrete cost scheme for inspection costs.

Table 25: 100 Hour inspection costs.

Aircraft Type	100 Hour Inspection Cost	SHP
4 cyl, fixed	\$650	<200
6 cyl, fixed	\$1000	>200
6 cyl, retract	\$1250	>200

Engine Overhaul

Aircraft engines require an overhaul at specified intervals, which is typically 2000 hours for small piston engines. The time between overhauls will be left as a variable to allow for engine life technology k-factor implementations. The approximate cost of overhaul for typical engine sizes and types were gathered from Lycoming publications. The cost of overhaul varies here primarily with the number of cylinders and the air intake and fuel mixing type. All turbocharged engines here are also fuel injected, thus giving a baseline cost schedule. This schedule is seen in Figure 73, with variation to SHP and the injection and air intake type. Engine overhaul cost translates to approximately \$5-\$20 per flight hour.

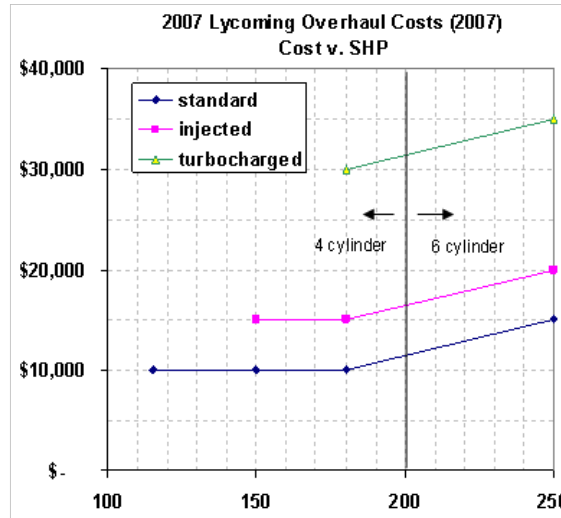


Figure 73: Engine overhaul cost schedule.

Unscheduled Maintenance

Unscheduled maintenance refers to any unexpected maintenance anywhere on the aircraft. Typical, hourly averaged costs for these maintenance areas are listed in Table 26.

Table 26: Unscheduled maintenance hourly cost estimates.

	Hourly Cost
Airframe	\$2
Avionics	\$2
Retracts	\$1

Receipts

The service provider receives payment for use of the aircraft and use of a pilot in the case of chartered, or air taxi, flights. The service provider can choose any method of payment, which is dependent on the type of operation. In the current day, rental of small aircraft is typically on an hourly basis, and the aircraft are often highly burdened, with little availability, meaning multiple day or even half day trips are rarely possible. But, in the case of future scenarios with rental car type operations, the service provider may want to explore the option of daily rates. This scenario can be further complicated if the service provider

has multiple locations, such that one way trips can be made. For air taxi flights, a trip of any length is performed by the chartered pilot on possibly separate drop off and pick up trips, creating higher aircraft availability, but with a smaller, richer customer base.

Cash flow Analysis

Cash flow analyses, or capital budgeting methods, are typically used to determine the viability of pursuing a given program. According to a survey amongst financial executives, the most popular methods include internal rate of return, net present value, and payback period (Graham and Harvey, 2002). In this case, the potential service provider entrepreneur or parent company must determine whether or not to set up a GAP service provider operation in a given location or set of locations. The aircraft fleet will be the primary sunk cost, acquired at year zero and relinquished at the end of the program period, a variable that is balanced between accepted lifetime (including acceptability by the customer), and the cost effectiveness. Aside from fleet depreciation, variation in residual value, and property tax, all other expenses and receipts can be considered on a yearly time period. For this reason, the most straight-forward method is to convert the aircraft acquisition cost, bundled with the residual value and depreciation into an average yearly payment. In this manner, the yearly expenses and receipts can be balanced with the yearly fleet payment to determine a one year cash flow. Thus the profit or loss for year n is:

$$P_n = rec_n - exp_n - (ACQ \frac{i((1+i)^N - R(N))}{(1+i)^N - 1} + \frac{1 - R(N)}{N} + \frac{1}{N} \sum_{n=1}^N R(n) \cdot taxrate) \quad (35)$$

The term rec_n includes all payments received for aircraft rental and chartering. The term exp_n includes the one year total of all expenses as explained in this section, excluding the aircraft financing, depreciation, and property tax, which are represented by the final three terms as one year average values. The one year cash flow can be expanded to any number of years up to the program length, but is primarily used to determine if the operation will be implemented or not implemented, the “go or no-go” decision.

6.1.3 Model Verification

The calibration and verification process associated with modeling of the GA service providers brings along with it a certain amount of uncertainty. There is limited evidence through which the model can be calibrated, for the service provider of a hypothetical advanced GAP has not yet been an artifact of history. The best that can be done, is to approach the process systematically and apply logical assumptions through which extrapolation can take place.

The “instructional” fleet, recorded by GAATA in fleet size and utilization, is used to calibrate the GAP service provider models. This fleet differs from a hypothetical travel-based rental fleet for several reasons. One is the enthusiasm of student pilots who are the primary makeup of users, which allows extremely high density scheduling. Students fight for every available hour and readily accept the less than pristine condition and comfort of training aircraft. Additionally, the majority of flights are contained within a short period of time, after which the aircraft returns to the same starting point for the next flight. These understandings will help drive a migration of assumptions towards a travel-based rental fleet, which in an ideal situation acts much like the car rental industry. But first, calibration to hard evidence must take place.

The total of recorded information concerning the instructional fleet amounts to just a few statistics, summarized for year 2005 as follows:

- 11,480 aircraft
- 3,187,000 hours
- 91% SEP by flight hours
- 87,213 student pilots
- 278 hours/aircraft
- 36 hours/student

The FAA lists only flight schools certified under FAR part 141, a rigidly structured program, of which there are approximately 488, but the majority of instructional facilities follow the guidelines of FAR part 61, which does not require FAA certification. Unfortunately, these schools are not tracked, and even if they were, they can include freelance instructors using a student’s aircraft for training.

Lacking specification about how the instructional fleet is distributed, a hypothetical population of schools was created. From the author's experience, it seems safe to assume that a typical flight school fleet consists of between three to six aircraft, go to as little as one, and as high as twenty. A gamma probability distribution with mode three and median four is used to randomly decide the size of the fleet at a given school. A population of flight schools is simulated by choosing from this distribution until the total number of aircraft matched the instructional fleet size published by GAMA. The resulting distribution of schools by fleet size is shown below, with a total of 2,538 schools and 11,482 aircraft.

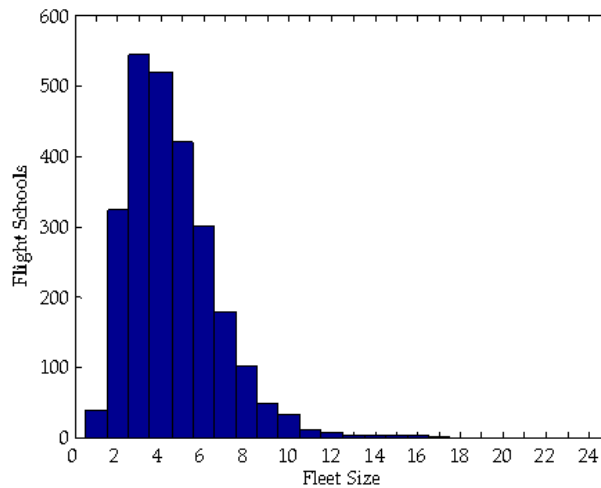


Figure 74: Estimated flight school fleet size distribution.

Next, the service provider model is used to simulate operation at each of these hypothetical schools. The average aircraft in the fleet was assumed to be 20 years old, with a cost of about 40% of the new price. Flight hours were assumed to be equally distributed to each aircraft, approximately 278 hours per aircraft per year. For calibration, the fixed costs, e.g. payroll and land, are adjusted until the majority of schools are seen to be profitable. The fixed costs are grown in proportion to the size of the fleet. Shown in Figure 75 is the simulated return on investment by fleet size. Single aircraft fleets return as unprofitable, and small schools are marginally profitable, but this should be expected as operation would follow a different business model, likely to be applicable to all smaller schools.

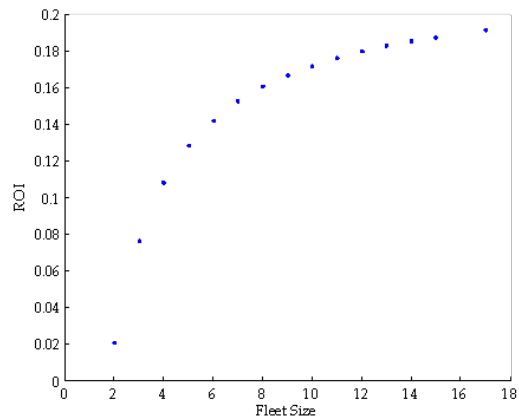


Figure 75: SP model: ROI v. Fleet Size.

While verification data is impracticable, one can observe the sensitivity of the model from the point of calibration to assess the validity of the model. First the fleet turnover rate - the time between fleet replenishment - is adjusted, under the notion that a widely used travel fleet might require a younger fleet. Simulated results for five and ten year fleets, plotted along with the calibrated results are displayed in Figure 76. The results are nothing less than expected, exemplifying the economical understanding that viability and volume go hand in hand.

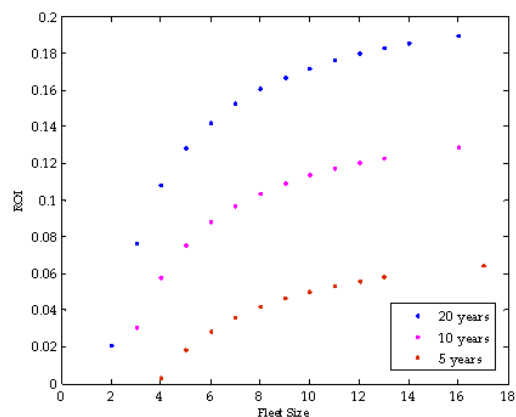


Figure 76: SP model: ROI v. Fleet Size, w/sensitivity to fleet turnover.

Aircraft availability is also an important aspect. An instructional fleet would be highly available because the flights are short and local, whereas a travel fleet would be much less

available, because flights are on the order of days. This effect is exhibited in Figure 77, where the allowed aircraft availability is varied, and the total operating cost (TOC) per hour is tracked. A travel fleet should be expected to exhibit less utilization, hence driving up the operating cost.

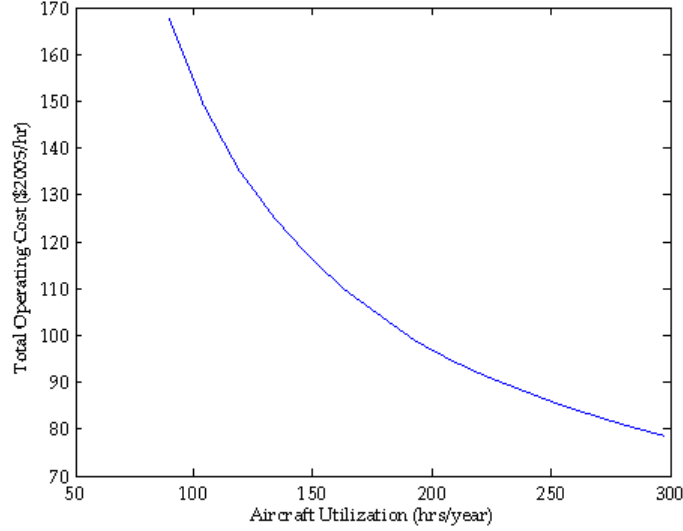


Figure 77: Sensitivity of TOC to aircraft availability.

The independent and combined effects of scheduling feasibility and economic viability are next studied through variation of the fleet loading variable, defined in Equation 32. As mentioned, low fleet loading results in a larger fleet for a given amount of demand, and hence the service provider will lose little demand. This comes with the burden to economic viability, as a large fleet requires greater returns to maintain.

A notional demand prediction is distributed spatially and temporally, scheduled, and examined for viability under a range of fleet loading settings (see Equation 32). The impact to capture fraction and fleet size are displayed in Figures 78 and 79, respectively, where the intermediate results without viability analysis are also shown. Without scheduling, capture fraction increases towards one as fleet loading is limitlessly decreased. At the same time, the fleet size rises towards infinity at an increasing rate. Once viability is implemented, the effect is realized, and as a result almost none of the demand is captured, as all service providers become non-viable and the GAP service becomes non-existent. This demonstrates

that the fleet loading variable can be used as a service provider control variable, rather than an assumption, and can potentially be optimized. As seen in this result, a fleet loading of approximately two, i.e. on average an aircraft is expected to accommodate two trips per week, provides optimal viable demand capture.

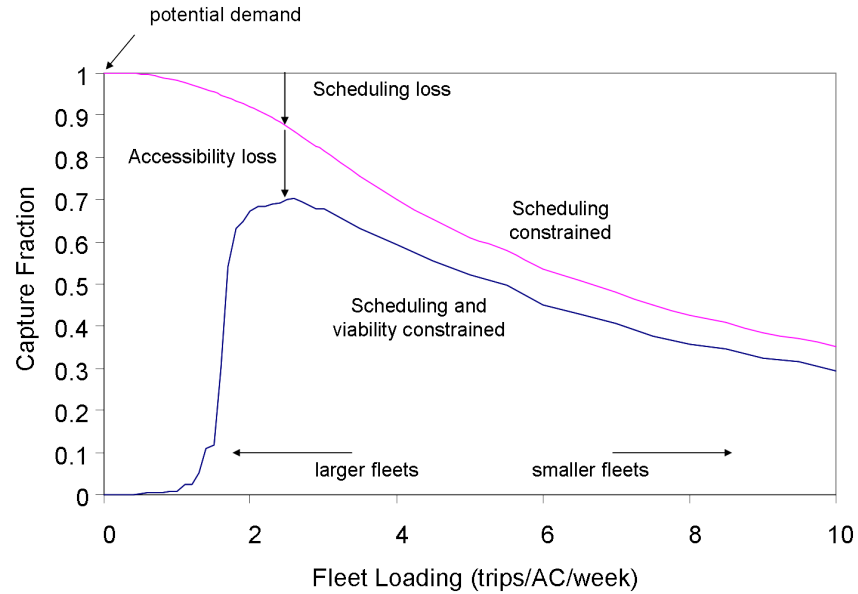


Figure 78: SP Model: Capture Fraction v. Fleet Loading.

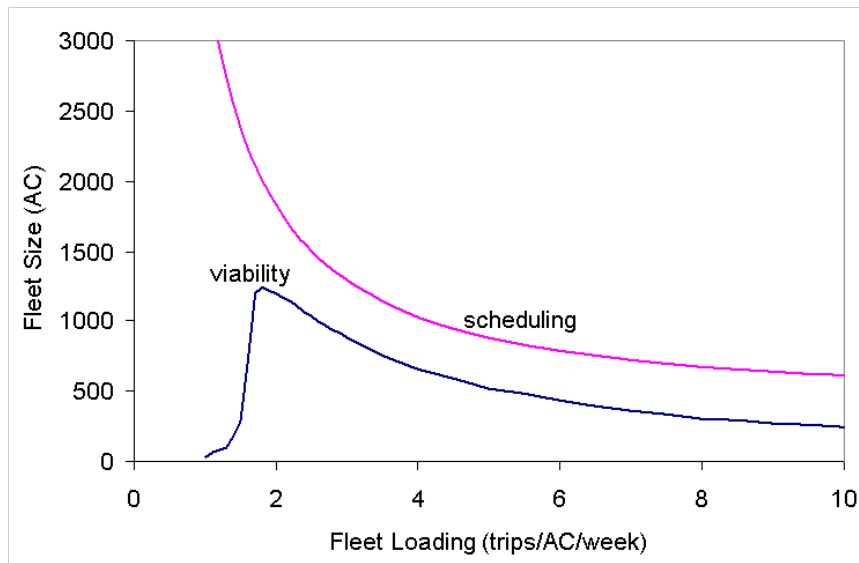


Figure 79: SP Model: Fleet Size v. Fleet Loading.

The effects of unscheduled maintenance may arise as a significant factor in the scheduling of aircraft, which in turn affects the viability of the service provider. To account for this effect, unscheduled maintenance is simulated by imposing a probability of unavailability. A probability, p_u , is defined which implies that on any given day, each aircraft has the probability p_u of being unavailable. The number of aircraft unavailable is then subtracted from the available aircraft, and is implemented in step four of the scheduling algorithm, Figure 69.

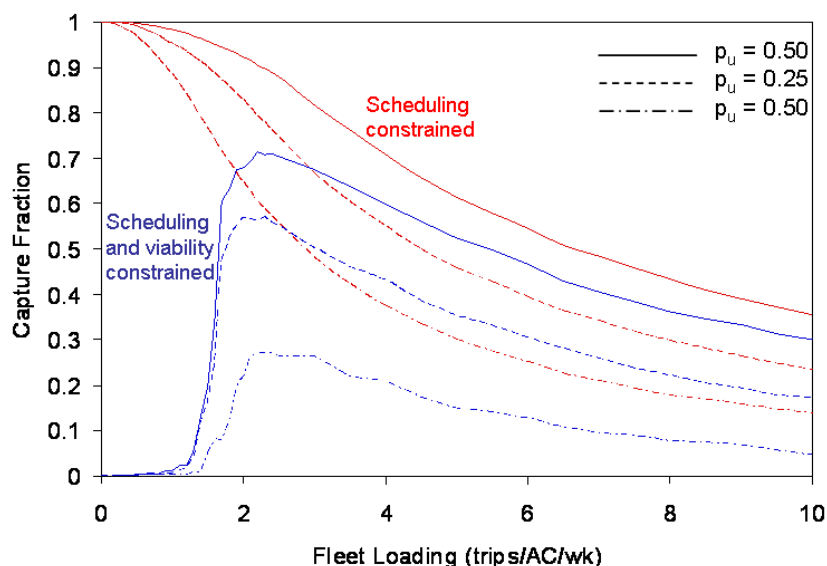


Figure 80: SP model results with simulated maintenance effects.

The results indicate that as the p_u grows, the detriment to viability grows at an increasing rate. While in this example, the service provider's mark up value and aircraft characteristics have remained constant, it would be of interest to understand how these variables might evolve under various scenarios of unscheduled maintenance. Assuming that a manufacturer might be able to estimate the robustness of their design, that is how often unscheduled maintenance is expected, perhaps as a function of the aircraft's cost, these interactions would be an interesting topic of future utilizing the completed analysis environment.

6.2 *GAJ Service Provider*

For GAJ aircraft, operations are focused on on-demand, per passenger service, commonly known as air taxi. Although there are significant differences, from an economical standpoint, the operation may be similar to that of a small, regional airline. For this reason, the operations cost estimate portion of ALCCA, which assesses the viability of commercial aircraft operations, is utilized.

The GAJ operates as an on demand air taxi service, with no pilot rentals. The fleet is assumed to be under a single operator and operates in a similar manner to a commercial airline. ALCCA is used to assess the service provider related costs. The indirect operating costs, IOC , and the flight operation costs, or pilot fees, FOC , are calculated by ALCCA. This requires an input assumption for annual utilization, U_{sp} , of each aircraft in the fleet. The direct operating costs, DOC , and acquisition cost, ACQ are calculated by equations 36 and 37 of section 4.2, repeated below.

$$ACQ = 0.000003 \cdot TOGW^{1.5067} \quad (36)$$

$$DOC = 0.0777 \cdot TOGW^{0.814} + FF \cdot COFL \quad (37)$$

The annual financing of the aircraft, FIN , is calculated by Equation 33. A number of “deadhead” flights, i.e. empty logistical flights, are assumed as a fraction, f_{DH} , of the total flight hours. Finally, the per passenger ticket price is set by an average load factor assumption, LF , and a service provider variable, $pMarkup$. The formula is shown below, where the term in brackets is the average total operating cost per service hour flown. Notice that $pMarkup$ defined here is slightly different than that defined for the GAP; here, mark-up is on TOC , for GAP the mark-up is on DOC .

$$p = \frac{1 + pMarkup}{pax \cdot LF} \left[(DOC + FOC) (1 + f_{DH}) + IOC + \frac{FIN}{U_{sp}} \right] \quad (38)$$

The service provider will try to utilize an aircraft of any size to or near its fullest capacity. As the size of the aircraft grows, flights between any origin and destination will decrease.

To the passenger, this creates an effective detriment to the on demand performance, thus a time penalty is implemented as the seating capacity grows. The penalty is zero for all aircraft three seats and less, and grows linearly to two hours for an eight passenger aircraft, where it is capped.

Finally, it is assumed that all GAJ air taxi demand is scheduled, and the total fleet size is calculated by dividing the total annual aircraft demand hours, which is estimated as the total passenger demand hours divided by seats and average load factor, by the annual aircraft utilization.

Chapter VII

RESULTS ANALYSIS

From the outset of this research, the goals have pointed towards building a system of systems model that captures the major supply and demand type interactions in a GA transportation system. The methodology for this process was laid out in Chapter 3, repeated in Figure 81. Having defined, bounded, and down-selected the systems representation for the GA systems design problem in Section 3.2, and explained in detail the systems models in Chapters 4-6, the process now picks up at step 6.

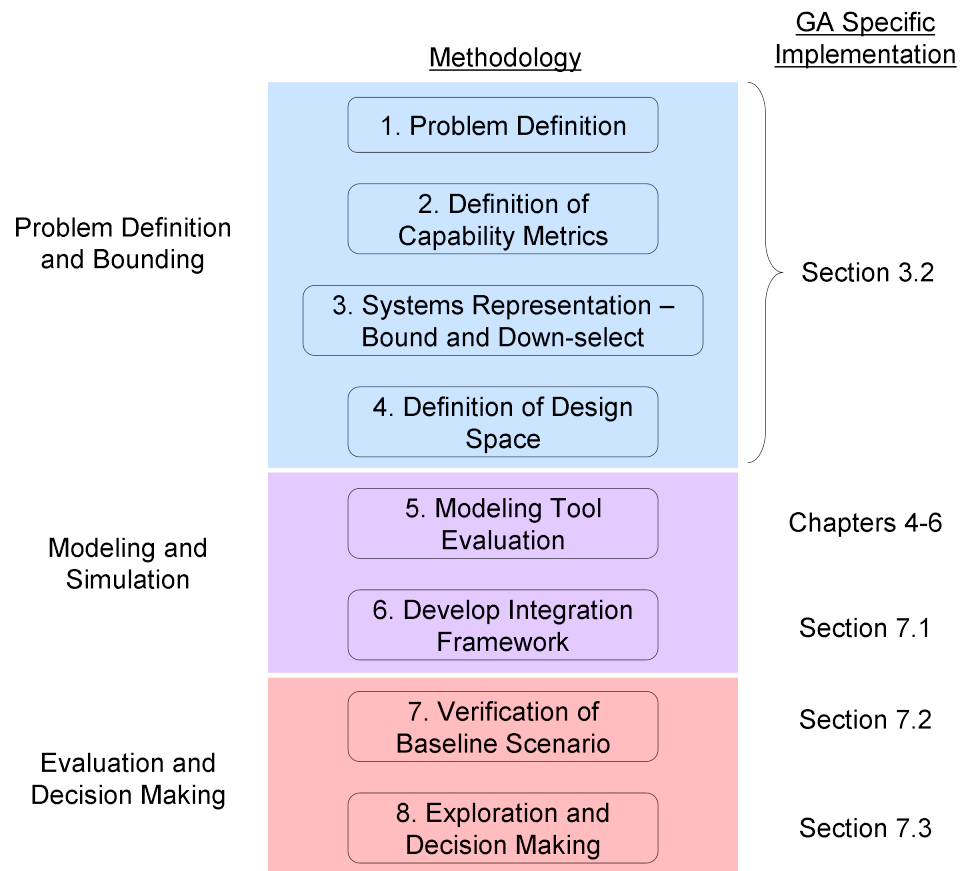


Figure 81: Methodology flow diagram, and locations of implementation.

7.1 Step 6: Integration Framework

In this section the blueprint for integration is presented, as well as a detailed mapping of variables and metrics throughout the model. Figure 82 indicates the blueprint conceptual flow of information through the analysis. From the aircraft engineer's perspective, the flow begins in the lower left, where a selection of aircraft design and requirements are implemented. Through the sizing and costing models, the operating and acquisition costs are calculated, and then used in the assessment of individual aircraft owners - if they own an aircraft and how much it is used. The operating cost also sets the aircraft rental rate at the service providers, after scaling it by the independent variable rental rate markup. While the markup can be independently lowered, resulting in increased demand, the service provider analysis accounts for this by calculating the revenues and costs - including the cost of fleet ownership. Finally, measures of captured demand - feasible and viable demand - in terms of usage and aircraft provide a basis for exploration.

Notice that in addition to the aircraft design related variables, the service provider can be independently defined by variation of the rental rate markup and fleet loading, which determines the local fleet size as defined by Equation 32. These variables can be changed without constraint, as their effects to demand, scheduling, and viability are accounted for. There are also a number of assumptions that can be varied to simulate scenarios. In general, any change to the system input variables (blue) can be assessed for the total impacts to the capability metrics (red).

ModelCenter 7.0 is used as the integration software, providing automation capabilities, including GAJ optimization as described in section 4.2.3. A detailed mapping of the variable and metric throughout the model processes is displayed in Figure 83, with the variables and metrics defined in Table 30. Execution of a single feed-forward analysis (excludes iteration on gray-dash feed-lines) on a 3 GHz Pentium D processor is approximately five minutes.

7.2 Step 7: Baseline Datum, Definitions, and Verification

The analysis process begins by establishing a reference datum, including specification of GAP and GAJ reference aircraft. Because the respective fleets are represented by a notional

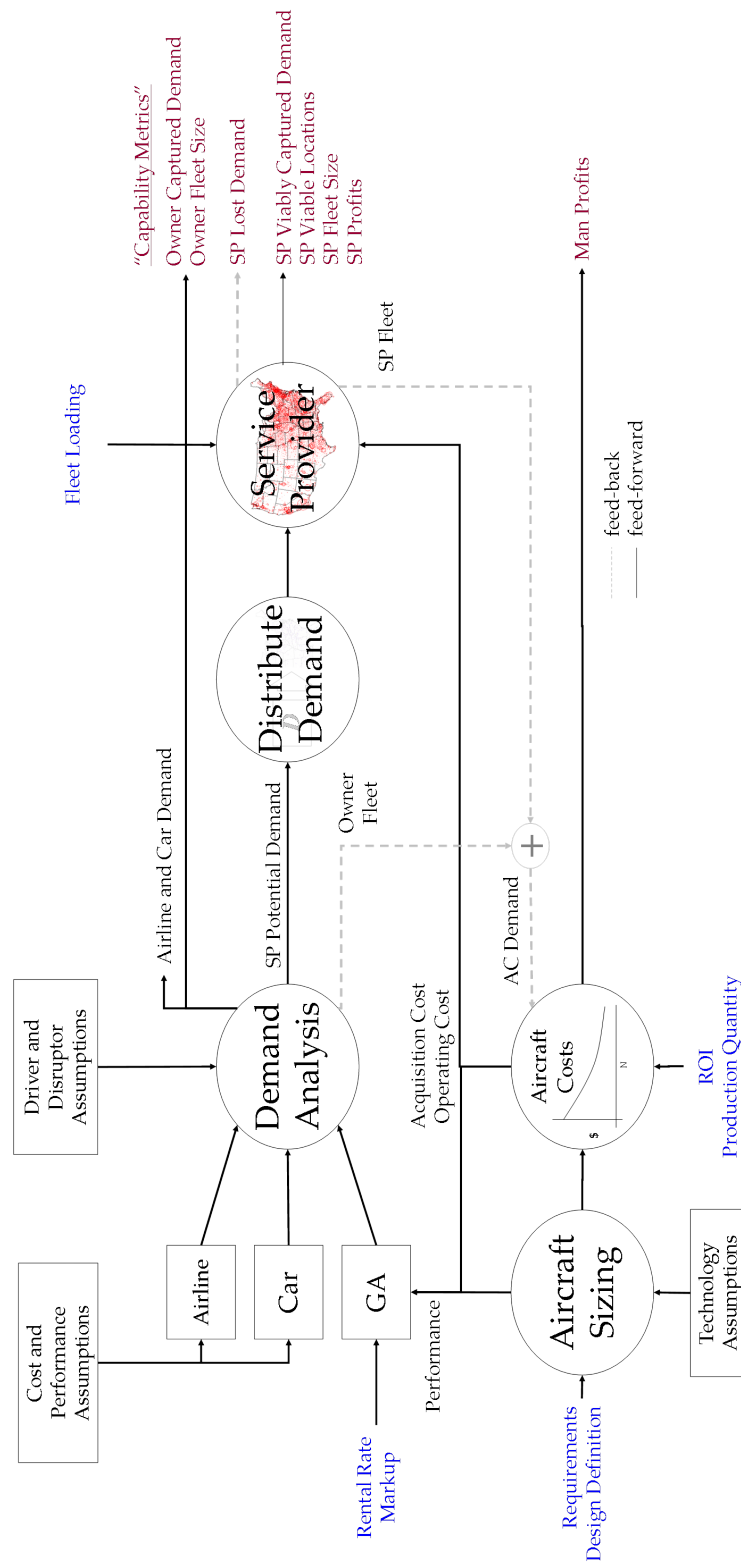


Figure 82: Integrated analysis blueprint: a conceptual viewpoint.

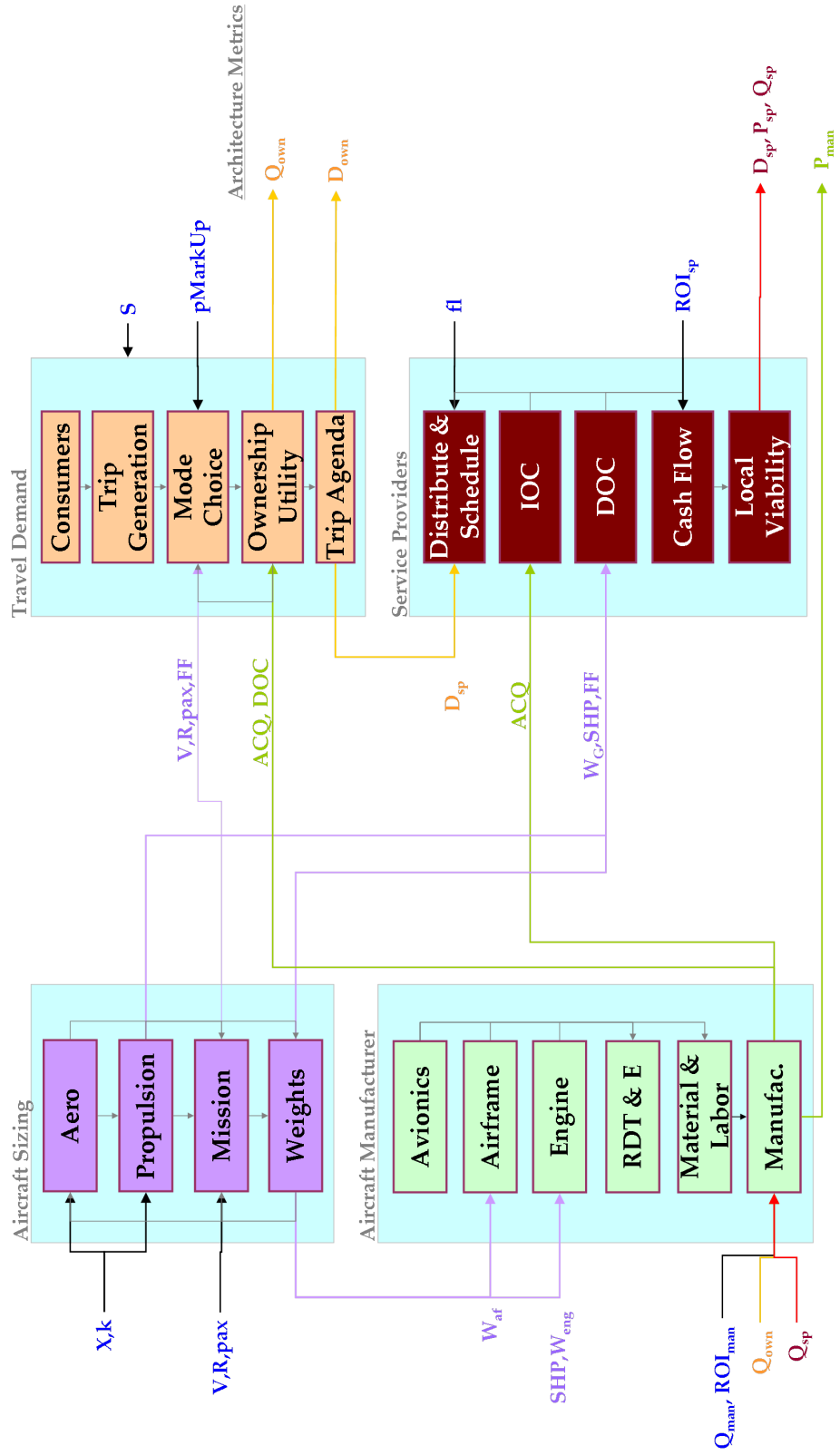


Figure 83: Integrated analysis framework: data flow.

aircraft, the examination of a parametric design space will be more revealing than a single design point. But first, a reference point must be established to which the environment is calibrated. The reference aircraft are created by calculating market share weighted values of the most popular existing GA aircraft. The specifics of the amalgamation process and aircraft data can be found in Appendix C. The resultant reference aircraft values are found in Figure 84, along with representative existing aircraft.

With these aircraft representing the GAP and GAJ fleets, demand is calibrated to year 2005 GA usage data found in GAMA (2006*b*) - see Appendix C for details. The demand has been summarized into three market categories: owner, rental, and taxi. The *owner* category is defined as individuals who purchase and use the aircraft through their own piloting. *Rental* usage is available locally through a service provider for a fee, and piloted by the user. *Taxi* usage is also available through a service provider for a fee, but piloted by a paid crew. GAJ aircraft are only tracked via taxi, as this is a market of current interest.

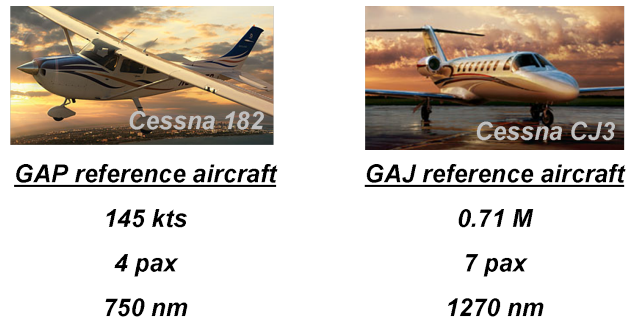


Figure 84: GA reference aircraft design requirements.

The demand calibration results are summarized in Tables 27 and 28, where for each market category the demand calculated for the calibrated reference aircraft, D_{ref} , is in person-trips captured per year. During the results analysis, all metrics will be scaled by the reference scenario values, and referred to as D/D_{ref} .

Table 27: GAP reference aircraft usage demand, with difference from calibration data.

	GAP reference demand (trips)	Error
Owner	1,729,000	+2.9%
Rental	44,300	-2.8%
Taxi	100,000	-4.3%

Table 28: GAJ reference aircraft usage demand, with difference from calibration data.

	GAJ reference demand (trips)	Error
Taxi	483,000	+0.3%

Next, the aircraft models are parametrized, in most cases by the design requirements to accentuate the contribution to the conceptual design process. The trends resultant from the evaluation of this design space are studied, first to verify and validate the capabilities of the integrated analysis, and then to extrapolate to hypothetical scenarios. Unless otherwise noted, design variables are held at the reference values indicated above. The GAP and GAJ studies are mostly examined separately, although an interaction study is also presented.

The models that compose the integrated analysis environment have been independently calibrated and verified for their behavioral aspects. In the previous section, calibration of the integrated environment was established by matching the aggregate usage demand under a representative aircraft design, with all models aligned to their baseline settings. This design point alone does not provide much information, and it is rather a parametric extrapolation from this calibration point which brings to light the capability of the integrated model.

The GAP can be defined by numerous design variables and requirements, but a comprehensible analysis is best achieved by selecting a small number of highly influential variables. Thus, the GAP design space is defined by the design mission cruise speed and payload requirements, which have been determined as the most influential. A discrete design space grid is created, indicated by Table 30, for which each point, the aircraft is sized, costed,

Table 29: Variable and metric definitions.

Variable or Metric	Baseline Value	Units	Description
Independent Variables			
pax	4	pax	design passenger capacity (200 lbs each)
R	750	nm	design mission range
V	145	kts	design mission cruise speed
X			aircraft design vector
$pMarkUp$	1.8		rental markup, sets rental price (scales DOC or TOC)
f	2	trips/wk/AC	fleet loading, sets GAP fleet size (annual demand/52/fleet size)
ROI	0.15		minimum return on investment
Q_{man}	853	AC	production lot quantity (5 year)
Scenario Variables			
k	1		aircraft technology vector
S			driver/disruptor scenario vector
Intermediate Metrics			
W_g	3342	lbs	takeoff gross weight
W_{af}	1671	lbs	airframe weight
W_{eng}	380	lbs	engine weight
SHP	263	HP	engine SL ISA rating
FF	92.4	lbs/hr	design mission fuel flow
$TOFL$	1423	ft	takeoff field length @ W_g
ACQ	172000	\$1995	acquisition cost
DOC	76	\$1995/hr	direct operating cost
p	137	\$1995/hr	rental rate
Capability Metrics			SP = service provider OWN = owner MAN = manufacturer
D		trips	annual demand
P		\$	annual or lot profit

and demand and supply availability are estimated. The primary metrics of interest are the captured demands for each of the three markets: owner, rental, and taxi.

Table 30: GAP aircraft and service provider design space definition.

variable	min	max	step	unit
<i>payload</i>	3	5	1	pax
<i>speed</i>	70	220	10	kts

The resultant demand metrics are plotted in Figure 85, as *demand to requirement mappings*. The variation to speed is graphically represented on the x-axis, the demand metrics are plotted on the labeled y-axes, normalized by the respective reference demand, D_{ref} , given in Table 27, and the variation to payload are indicated by marker type. Unless specifically noted, the term demand implies captured demand, and is typically given in the normalized form. Each point is the result of a single execution of the analysis environment, which alone does not reveal much information, but together the characteristic demand trends of the GA transportation system are approximated.

For example, the design speed, which clearly has a strong impact on demand, is a characteristic market differentiator. The taxi market peaks at high speeds, while the rental and owner market peak at low speed. These phenomena are results of the simulated interaction of consumer agents, who have certain desires and constraints, and the supply of travel resources, which are bounded by physical feasibility and economic viability.

In the case of the taxi market, the expensive pilot surcharge has limited the service to high income customers, those with a high value of time, thus driving the best design towards a high speed configuration, around 180 kts. Lower speed aircraft do not attract these customers, as their door to door time is highly valued, and higher speed is limited by the exponentially increasing costs resulting from a similar increase in weight and required power (see Figure 38 for sizing and costing trends).

For the rental market, it seems that the majority of consumers prefer a moderate tradeoff of speed and the resultant cost, settling around 130 kts. The demand is again degraded at

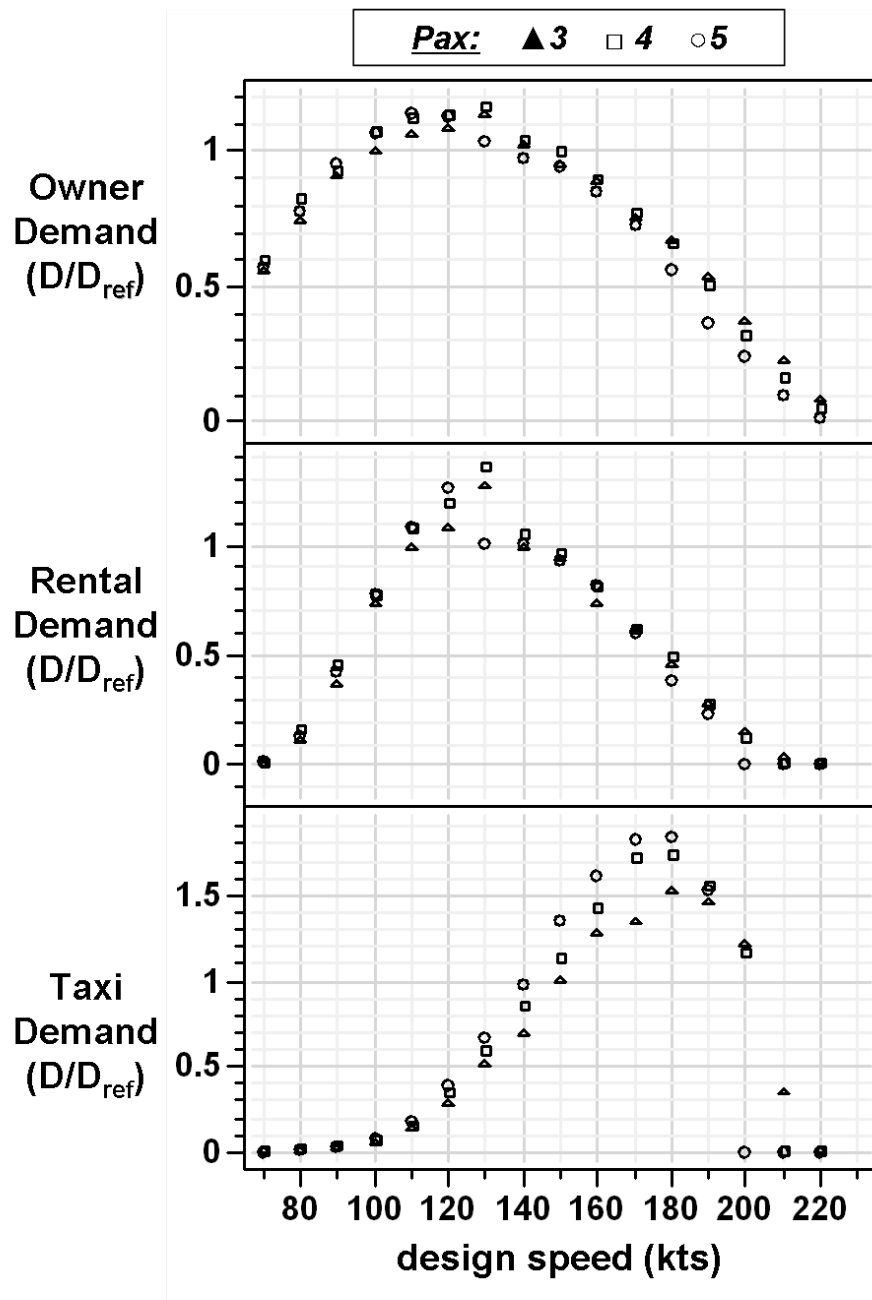


Figure 85: Baseline design space: Demand v. design speed.

lower speeds by increasing door to door time, likely approaching that of an automobile or commercial airline, and at higher speeds by the increasing costs. In the rental and taxi cases, economic viability of the service provider is required, which is shown to be possible here.

The owner market also indicates a demand peak at low speed, around 130 kts, although the decision process is slightly different, as no service provider is involved. Instead, owners justify the cost of the aircraft over a long period of usage. Because the costs of ownership are considerably expensive to the majority of consumers, the performance of the most highly demanded aircraft is limited. This is also seen by a distinct balance in the payload requirement (see Appendix c, Figure 136 for extended payload results); long term usefulness demands that many potential payloads can be carried, i.e. that the aircraft is useful for “family” trips. Smaller aircraft begin to lose this capability, while the marginal utility of a fifth seat is apparently less than the cost incurred to the design. Similar observations can be made for the other markets.

The taxi demand trends show that a five seat configuration is slightly more desirable and viable at the optimal speed of 180 kts. Since the analysis environment is limited in aircraft representation, i.e. GAP is represented by a single design, the resulting demand peaks point towards the single most desirable design. In reality, each market will be further segmented. While future work should address these phenomena, the current analysis can provide further information with some implied translation. For example, in Figure 86, the speed and payload requirements are mapped to taxi demand contours. Also indicated is the path of optimal design speed if the variation of payload is forced, or vice versa, indicated by the gray line. This line implies that design speed and payload should be inversely varied as niche markets are to be pursued, i.e. increasing payload should be accompanied by a decrease in speed.

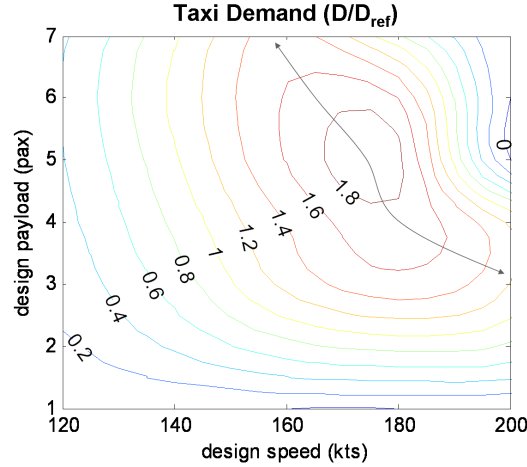


Figure 86: Taxi market requirement impact correlation.

Returning to the trends in Figure 85, a notable difference between the owner market and the service markets' trends is that the demand peaks tend to be much sharper for the latter. Note for example the very sharp demand peak at 130 kts for the rental market, whereas the owner market peak is relatively indifferent from 110-130 kts. Also, observe what happens as the five seat taxi configuration is designed faster than 200 kts. The rapidly rising cost of the larger aircraft creates a sudden non-viability for the service provider. As the service markets lose demand, local service providers pass below the point of economic viability, and thus go suddenly from servicing a considerable number of consumers to being non-existent. The owner only needs to interact with the manufacturer, for which this *volatility* is less apparent, as they reach all consumers from a centralized operation.

Another perspective is gained by observing the *market demand space* plots, as exhibited in Figure 87. In each plot the normalized captured demand of the indicated markets are plotted against one another for each point in the design space. This representation of the market demands allows the observer to put aside the design characteristics, and focus on how the markets interact with one another. For example, the plot of taxi against owner demand shows that as demand in one market grows, the demand in the other declines. In effect, a single GAP design cannot simultaneously capture both markets. In some cases of

design, this is considered a *Pareto frontier*¹. But, while one might consider a *compromise* design, i.e. a design that attempts to partially capture both markets but maximizes neither, implying competition dynamics might lead one to consider this trend as a sign of a *market bifurcation* and deem the two markets as *incompatible*. That is, through competition, a compromise design would be undermined by a competitor's aircraft that targets only one market - the competitor's aircraft would be solely designed for one market and thus likely to be significantly more appealing to that market than the compromise design.

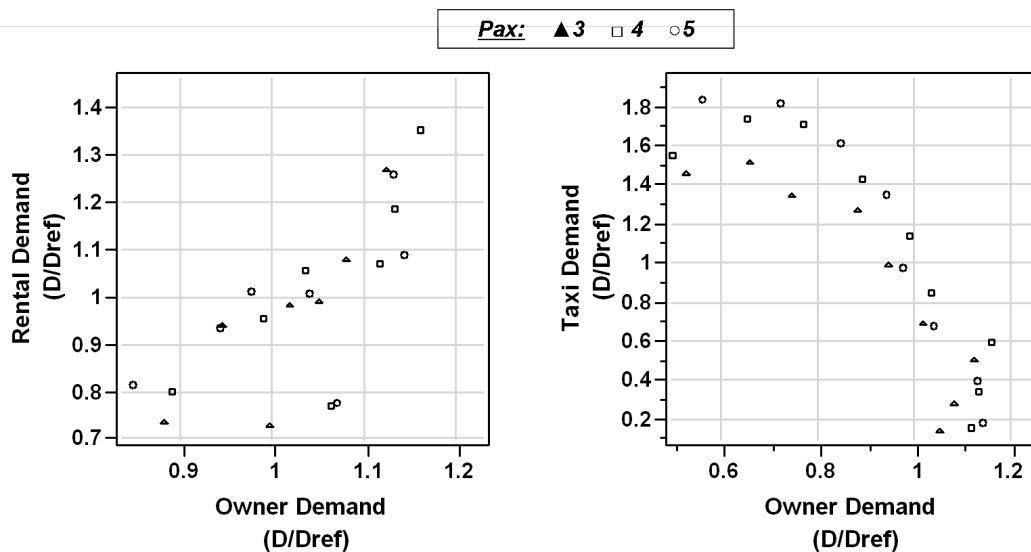


Figure 87: Baseline market demand space plots.

On the other hand, the plot of rental against owner demand shows both increasing simultaneously, resolving to a point of common maximality. These *synergistic markets* could likely be pursued by a similar aircraft design, which was seen to be the case earlier. Even with slight differences, e.g. payload capacity or engine upgrade, the manufacturer can focus on creating a mostly common aircraft, with variants for the two markets.

Based upon the observations in this section, there is some evidence that the environment

¹ A design point within a given set, each represented by a vector of selected objectives is considered *Pareto optimal* if there is no other point in the set for which all objectives can be considered better. If such a point existed, it would be said to be *Pareto dominant* with respect to the other point. The subset of Pareto optimal points is termed as the *Pareto frontier*. If this subset is removed from the original set, then the Pareto frontier of the remaining set is called the 2-Pareto frontier. Subsequent repetition of this process results in the set of *s-Pareto frontiers* (Mattson and Messac, 2003).

provides an approximation to reality. First, the four seat configuration was seen to capture the most demand, which has been and continues to be the most popular and most desired GA configuration (Turnbull, 1999; GAMA, 2008). The trends associated with the design speed are also characteristic of reality. Air taxi services², tend to use high performance aircraft, such as the SR-22 (180 kts), whereas the average owner or renter is most likely to be flying a moderate speed, affordable aircraft, such as the Cessna 172 (120 kts). A survey of owners in 1976 also shows that air taxi operations tend to be performed at higher speeds than the owner and rental operations (Vahovich, 1976). A comparison of the predicted “best speed”, i.e. the speed which results in the maximization of demand, to that of the “typical” aircraft mentioned earlier and to that of the owner survey is displayed in Figure 88. The model matches well in trend and magnitude to the “typical” aircraft, while the comparison to the owner survey shows a similar trend yet a consistently higher prediction. This is possibly due to the fact that the model speed corresponds to the aircraft’s design speed, and the survey corresponds to the question of what speed is normally flown, thus factoring in variation of off design speed choice, instrument calibration, and aircraft age.

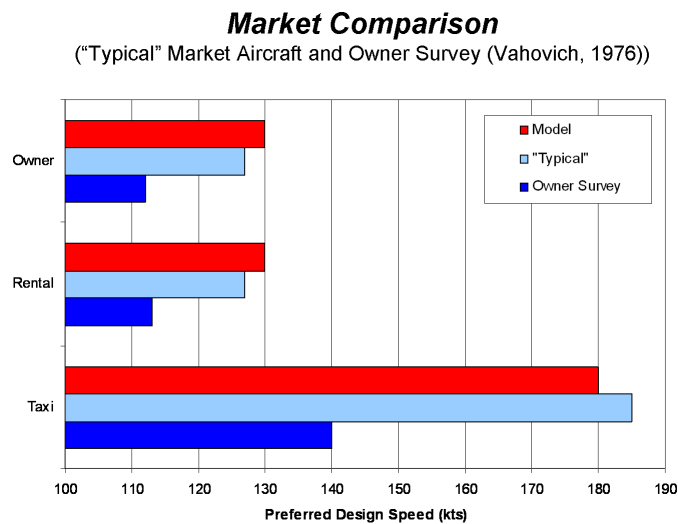


Figure 88: Market speed preference validation results.

In reality, individual owners have the opportunity to choose among a variety of aircraft,

²For an example, see the details of SATSair's operation at www.satsair.com (acc. 05/2008).

whereas rental and air taxi operators will tend towards composing their fleet of a smaller number of aircraft types. Hence forth, the rental and air taxi fleet will be assumed to be representable by a nominal design, whereas the owner market will be studied in more detail in an attempt to validate the differentiation of aircraft characteristics by consumer characteristics. The best measures of the consumer and design characteristics, due to availability of validation data and due to relative effect of the characteristics, are the consumer's income class, and the aircraft's design speed and payload. Historical data is summarized from three primary data sources, the GAMA shipment reports (GAMA, 2006*a*), the GAATA Survey (FAA, n.d.), and the FAA 1976 Owner Survey (Vahovich, 1976), which together form a "proxy world" for the verification and validation process.

First, the owner modeling results are presented in further detail, by observing the utility of ownership (see Eq. 29) for various income brackets. Recall that the utility of ownership is used by the consumer to determine their ownership status, and weighs the benefits of utilization (time and cost savings in relation to the next best available option) against the annual costs of ownership (acquisition cost, insurance, etc.). The consumers are divided into income brackets ranging from 25k to 175k and above, in 1995 dollars. Under the baseline settings, no owners were found below the 25k income level. In Figure 89, the normalized, or relative utility of ownership is tracked as the aircraft's design speed is varied. For each income bracket, it can be implied that the design speed at which the peak of the relative utility represents the most desirable aircraft for that group. In general, it is seen that the best design speed increases with the consumers' income, as is expected.

For each income class, the number of owners is tracked at the best speed setting. Summarizing this data provides insight into how the model predicts the differentiation of the market by income class and speed. This summary is found in Figure 90, where the predicted market share (fraction of aircraft owned) and the most desired speed is plotted against income class. As seen previously, the best design speed tends to increase with income, and somewhat unexpectedly, the market share tends to be considerably higher at lower income classes. This is due to the much larger population of these income brackets, as in 1995 approximately 95% of all households had income below 100k.

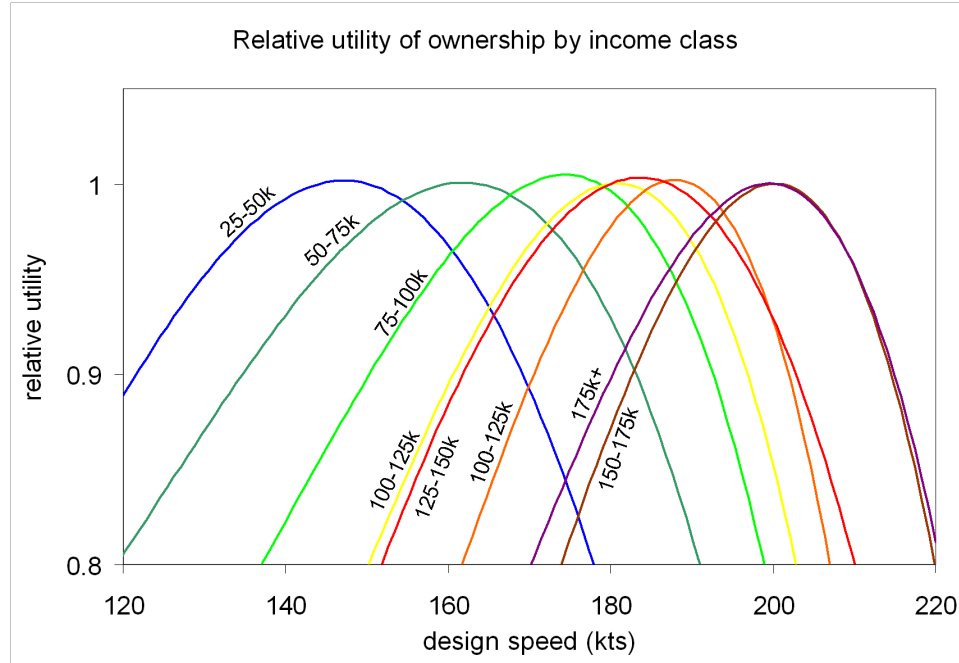


Figure 89: Model prediction: owner utility by speed and income bracket.

The predicted behavior is next compared to the historical data, with respect to the speed and income characteristics. The characteristics of new aircraft shipments are used to verify and validate the market differentiation by speed class. The design speeds for each of the ten most popular SEP aircraft from the five year period of 2001-2006 are collected. This selection of validating data is used as it represents what aircraft are desired by new consumers, and should also be fairly representative of the existing fleet. In Figure 91, the cumulative market share of aircraft at and below the given speed is plotted, as predicted and as found in the GAMA shipment reports. The model results tend to agree well from this perspective, as much as one might expect from a model of a highly complex system.

A similar validation process is performed by comparing the cumulative market share up to a given income level. The validation data is found in Vahovich (1976), the only data of its kind that could be found, and has been adjusted for inflation. The resulting comparison is shown in Figure 92. Again, the model prediction agrees well with the validation data.

Finally, the payload requirement is varied in a similar fashion as was done with the speed requirement, and the number of predicted owners is tracked. The model results are compared to data in (FAA, n.d.), which summarizes the existing SEP fleet by payload into

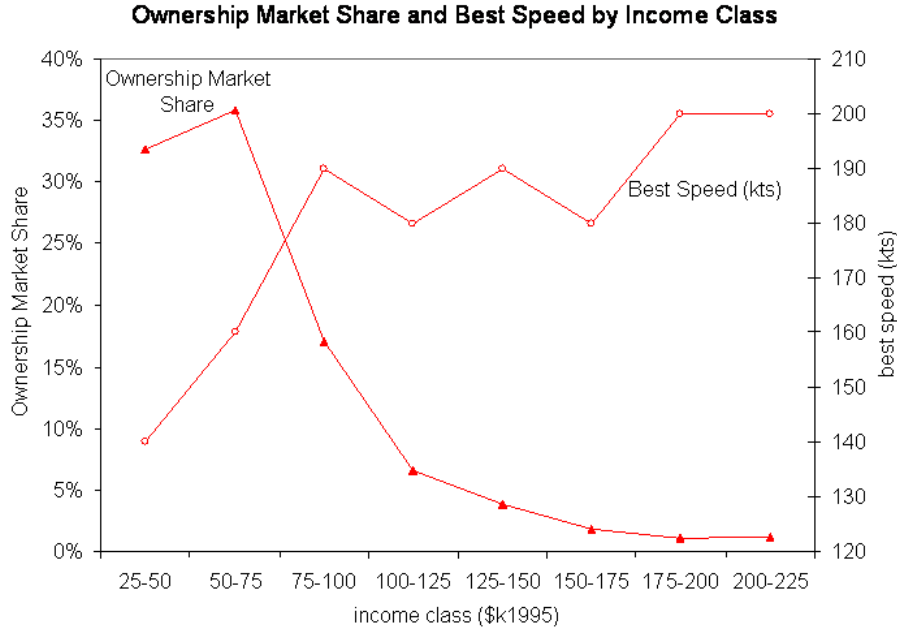


Figure 90: Model Prediction: Speed preference and market share by income bracket.

two categories: 1-3 seats and 4+ seats. In Figure 93, the validation market share is compared to the model prediction in two different manners.

First, the model results are categorized by payload in the same manner as the validation data. The discrepancy is not large, but a justification is made for a more fair comparison. First, it is well known in the GA world that the statement of “4 seats” is not always corresponding its practicality. While it is possible to fit four passengers, it is very uncomfortable and limits additional payload, i.e. luggage, and possibly fuel. Additionally, the aerodynamic shaping of the fuselage, which drives a gradual, rather than abrupt tail end of the fuselage, along with the minimum width requirements for which the rear seat can be considered as have a capacity of two, will likely cause a manufacturer to treat any aircraft with a rear seat as a “4 seat” aircraft to increase its attractiveness. Thus, three seat aircraft are very few, and likely make up a small portion of the 26% recorded in the validation data. On the other hand, the modeling process does not see these anomalies, and the manufacturers and consumers alike see a significant difference in the three and four seat aircraft. Through this reasoning it seems fair to assume that the number of “3 seat” aircraft in the validating data

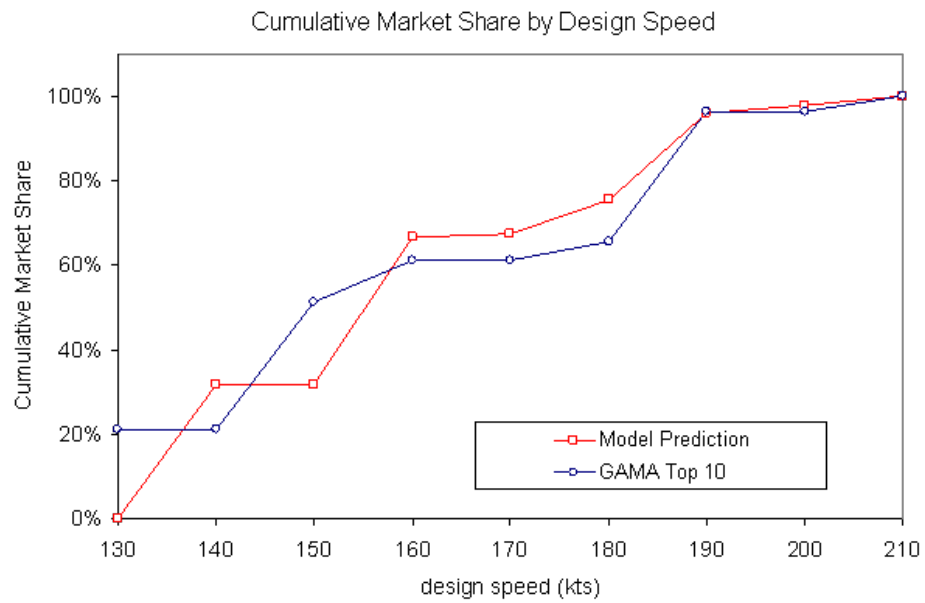


Figure 91: Model Validation: Cumulative market share by design speed.

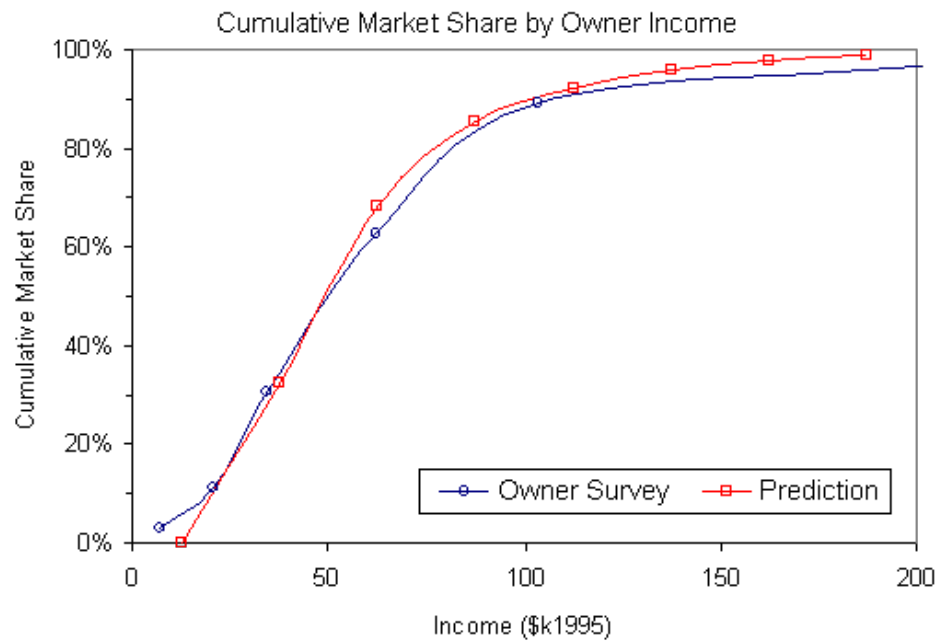


Figure 92: Model Validation: Cumulative market share by owner income.

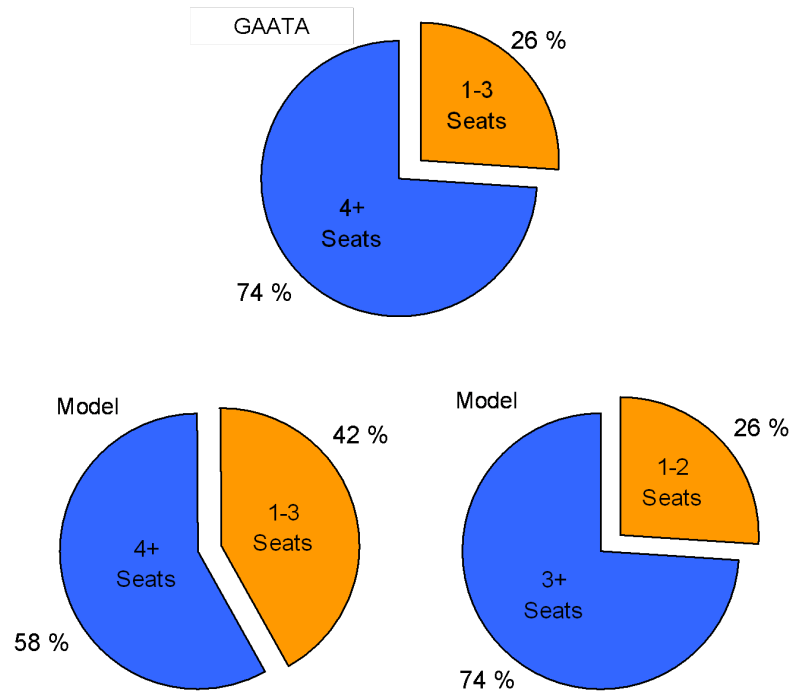


Figure 93: Model Validation: Market share by design payload.

set is negligible, and that in the model results, the three seat aircraft should be grouped with the four and above category. Essentially, the comparison reduces to those aircraft with a rear seating compartment, and those without. Under these assumptions, the model agrees more closely with the validation data.

Up to now, the model has been studied for its ability to predict reality, a process of gaining assurances of if the results are dependable and an understanding of how results should be interpreted and what caveats to follow. Validation data is not easily achieved, definitely not by experimentation, and a “proxy world” must be built from supporting historical data. The validation sets used focused on providing the trends of market differentiations by the most influential characteristics, namely income class, design speed, and design payload. Validation of a complex system cannot typically be affirmed by a hard threshold, and it is rather through the eye of the user to agree that the trends and relative magnitudes of the model sufficiently match the validating data. Accepting the model, it can then be utilized as a tool for extrapolating from the conditions of normalcy, and seeking answers to some questions of interest, the focus of the proceeding section.

7.3 Step 8: Exploration

A number of hypothetical scenarios have been derived for the GAP and GAJ travel systems. In each of the implemented scenarios, the results are carefully studied, and strategies are demonstrated that can be used in translating the analysis results in to design decisions.

7.3.1 GAP: Technology Studies

According to Downen and Hansman (2003), the difficulty of obtaining a pilot's license, including both the process and required skill, and the costs associated with utilizing GA, especially high performance aircraft, are of greatest hindrance to its utility as a travel mode. To address this issue, two hypothetical technologies are simulated, dubbed easy-to-fly (E2F) and advanced performance technologies (APT). *E2F* is modeled by a 10-fold increase in the population of licensed pilots, simulating dramatic advances in avionics and control implementations. *APT* is modeled by improving the specific fuel consumption, fuselage drag coefficient, and specific engine weight each by 20% of their baseline values. The combination of technologies is also studied, and referred to as *APT+E2F*. These technologies are initially assumed to have no cost penalties (this is approximately in-line with the attributes of NASA's Next Generation GA aircraft (Moore, 2003); technology cost sensitivity is studied in the following section).

Table 31: GAP technology definitions.

Technology	Description	Modeling
Advanced Performance Technologies (APT)	A suite of airframe and engine technologies aimed at improving the aircraft's performance.	Improves power specific fuel consumption, fuselage drag coefficient, and specific engine weight each by 20% of their baseline values.
Easy to Fly (E2F)	On-board and central flight control and navigation systems which significantly reduce the difficulty of operation.	10-fold increase in the population of licensed pilots.

Initially the magnitude of impact the technologies have on the market demands are gauged in the market demand space plots, Figure 94. For clarity, only points that are dominant in the Pareto sense, i.e. there is no other point that has greater demand in both

markets, are included for each technology scenario. Note that this eliminates the majority of points when the markets are synergistic, indicating low tradeoff importance, and vice versa for incompatible markets.

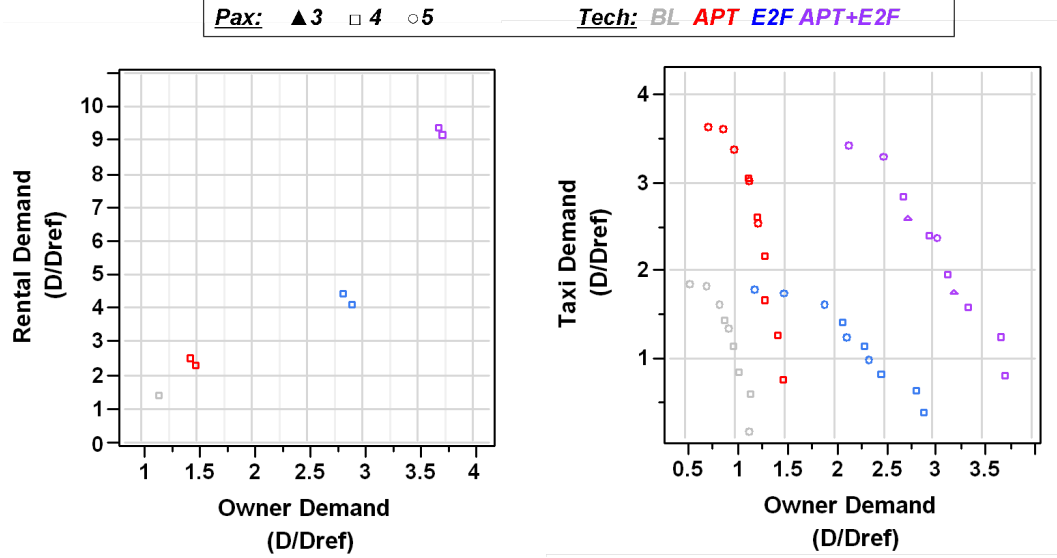


Figure 94: Market demand space plots: baseline and with technology implementations.

Studying the plot of rental against owner demand (left), it is clear that both of these markets receive significant gains from each technology, although E2F is considerably more effective than APT. It is also clear that the technology combination, APT+E2F, is much more beneficial than the linear combination of APT and E2F. This is especially true for the rental market, where the best gain is approximately 70% from APT, 200% from E2F, but 500% from APT+E2F. A similar trend is seen with the owner market, approximately 35% from APT, 160% from E2F, and 240% from APT+E2F. In general, the owner market is less affected by technology implementation, although the benefits are still very high. This is likely because, whereas an owner always has the opportunity available, a renter only has the opportunity available when a local service provider is present. Thus as technologies are implemented, local service providers “pop-up” due to the increased number of pilots, and the desirability of the aircraft.

Moving on to the plot of taxi against owner demand (right), it is first apparent that the taxi market receives no gain from E2F, and is actually degraded due to a small loss

in customers, now pilots, to the rental and owner markets. While the APT technology is beneficial to both markets simultaneously, the market compatibilities are not affected. One might think that APT would help to bring the markets together, creating a faster aircraft to satisfy both markets, but a look at the demand to requirements mapping, Figure 95, shows what actually happens.

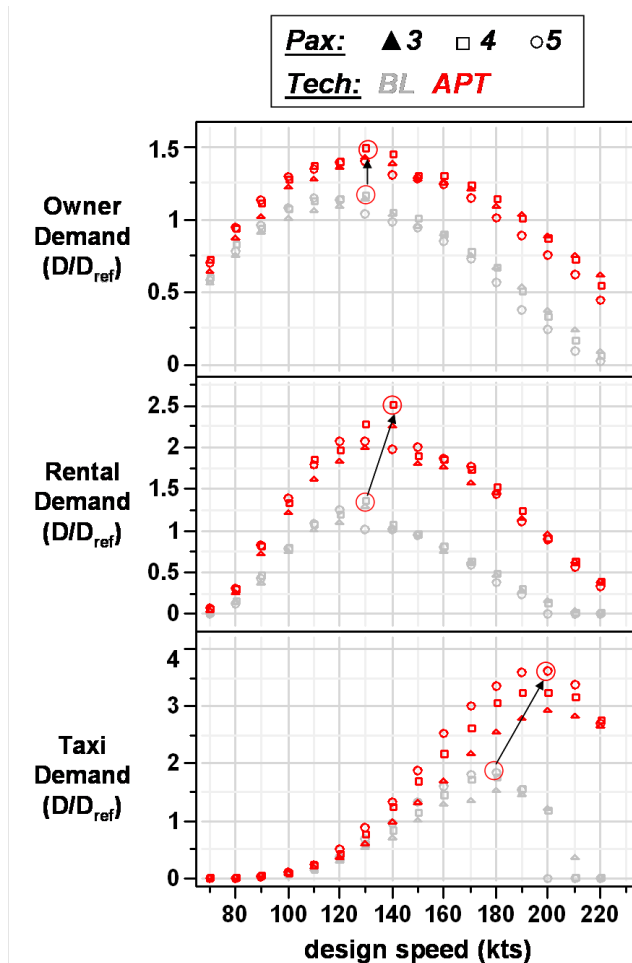


Figure 95: Normalized market demand: BL (gray) and APT (red).

For the taxi market, the design speed where the demand peaks increases when going from the baseline to APT scenario, indicating that the technology is used to *increase the performance*. On the other hand, the owner demand peaks at the same speed in either case. This does not seem intuitive, considering that the demand increased significantly, but no performance was gained. Looking at Table 32, it becomes apparent what is happening.

Here, the requirements settings and resultant aircraft cost metrics corresponding to the maximum demand for each market and technology level have been gathered. The acquisition and operating cost values of the owner market indicate that this market implements APT as an *effective cost reduction* technology, while keeping the performance constant. Thus the technology allows reduction to weight and fuel burn, translating to lower acquisition cost and direct operating cost, at a constant level of performance. These results help to demonstrate how a designer can answer a simple question when considering implementation of a performance technology: *do we use the technology to improve the performance capabilities, or reduce costs?*

Table 32: GAP requirements preference and cost characteristics.

owner	pax	speed (kts)	DOC (\$/nm)	ACQ (\$k)
BL	4	130	0.44	276
APT	4	130	0.34	222
E2F	4	120	0.43	254
APT + E2F	4	130	0.34	222

rental	pax	speed (kts)	DOC (\$/nm)	ACQ (\$k)
BL	4	130	0.44	276
APT	4	140	0.35	237
E2F	4	130	0.44	276
APT + E2F	4	140	0.35	237

taxi	pax	speed (kts)	DOC (\$/nm)	ACQ (\$k)
BL	5	180	0.78	755
APT	5	200	0.65	586
E2F	5	180	0.78	755
APT + E2F	5	190	0.58	489

Previously, technology implementations were simulated in an ‘on/off’ fashion, and without the consequence of cost penalties. Here, the technologies are implemented in a continuous fashion, and later cost penalties are assessed. Unless otherwise noted, technology is applied to the GAP reference aircraft (4 pax, 145 kts, 760 nm).

The first study is based on APT, but whereas before the specific fuel consumption, engine weight, and fuselage drag coefficient were at a fixed reduction of 20%, this percentage is continuously varied from 0%, i.e. the baseline, to 60% in 10% intervals, and referred to as *APT strength*. For each setting, the design speed resulting in maximum demand for each

market is found, to the nearest 10 kts. This best design setting and the resulting direct operating cost are plotted against the APT strength in Figure 96.

Recall in the previous section, where APT was defined as strength 20%, that the taxi market used APT to primarily enhance performance, and the owner market used it to primarily decrease the costs. This trend is again seen here, and now seen to extend out to APT strength 30%, where finally the owner market begins to realize APT as a means of improving the mission design performance.

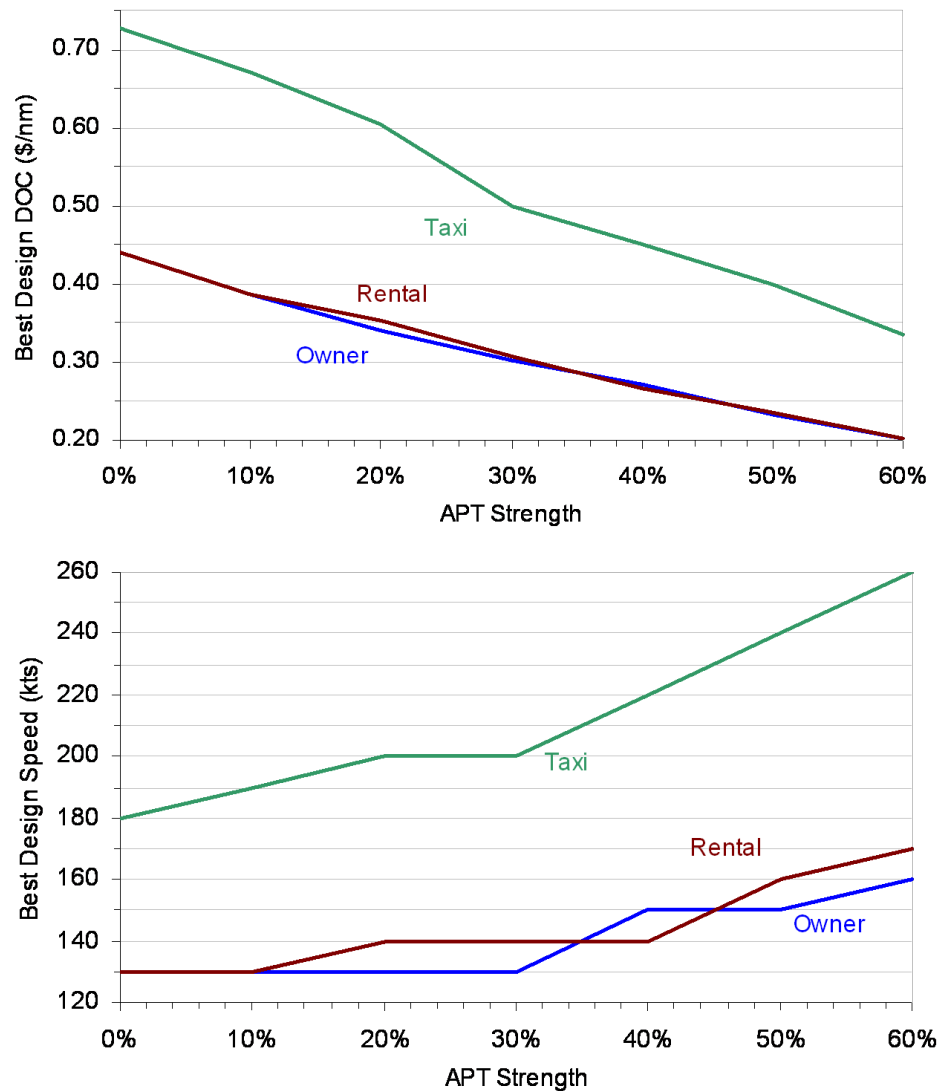


Figure 96: APT strength study results.

Over this broad range of APT strength, all the markets use APT to both increase the design performance and to decrease the operating costs. Yet, whereas the owner and rental markets put emphasis on cost reduction, the taxi market leans heavily towards increasing design performance. This makes sense because taxi consumers tend to have a high value of time, putting cost at a lesser importance. Additionally, the benefits of APT will have greater effect at higher speed, as drag and power increase by the square and cube, respectively, of the design speed.

Next, a simplified version of APT is examined with the cost penalties included. In Figure 97, the normalized demand contours of the owner market are plotted with variation of an engine fuel flow variable (x-axis) and cost variable (y-axis). These variables, referred to as *k-factors*, simulate the implementation of a technology through a linear scaling of a disciplinary metric, in lieu of implementing or having available a detailed technology analysis capability. The variable *kbsfc* is a k-factor that linearly scales the specific fuel consumption, and *kCeng* similarly scales the calculated cost of the engine after mission sizing occurs. In both cases, a k-factor value of 1 corresponds to the baseline, and a lower value indicates an improvement.

This method of analysis could be used in a technology planning scenario. For example, consider a scenario where a decision maker wants to consider implementation of the fuel flow reduction technology, but wants to know what the cost penalty must be limited to if a minimum 5% increase in demand from the reference demand is desired, corresponding to $D/D_{ref} = 1.05$. The region of the k-factor space which satisfies this criterion has been highlighted in green, indicating that any combination of k-factors within this space is considered satisfactory. For example, a specific fuel flow reduction of 10% ($kbsfc = 0.9$) is satisfactory as long as the specific engine cost remains within 12% ($kCeng = 1.12$) of the baseline engine. During the technology maturation process, this method can be used to guide trades in cost and further fuel flow improvements.

The drag reduction portion of the APT technology is considered in Figure 98, where *kcdof* scales the fuselage drag reduction k-factor, and *kCaf* is the fuselage cost k-factor. The hypothetical demand increase goal of 5% is again set, and the region of satisfaction is

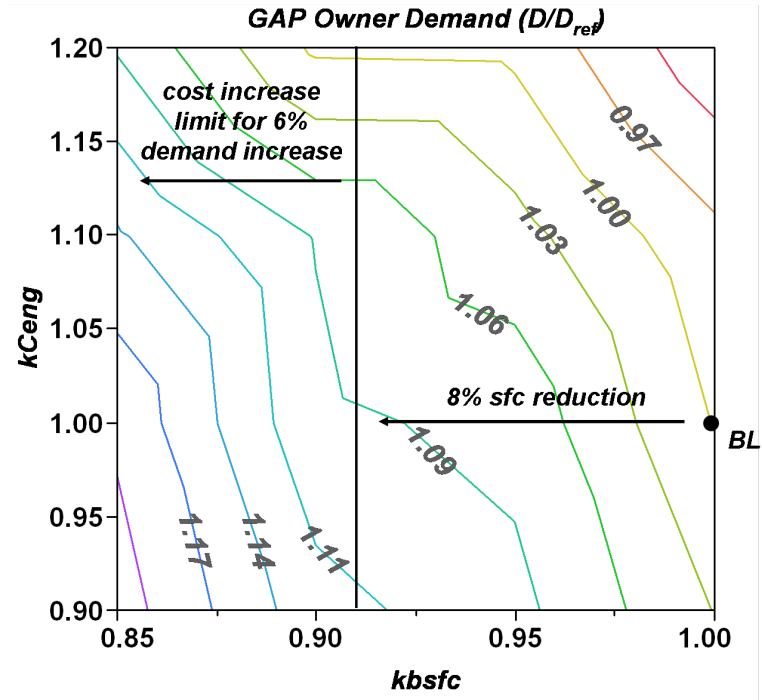


Figure 97: Owner demand contours with sensitivity to engine technology k-factors.

highlighted green. Upon immediate inspection, the technology seems much less lucrative, but keep in mind the a unit percentage increase in airframe cost is typically larger than that of the engine.

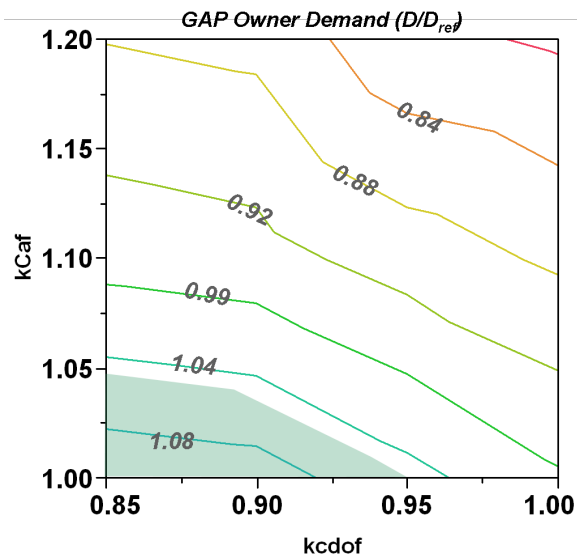


Figure 98: Owner demand contours with sensitivity to airframe technology k-factors.

A manufacturer considering the choice of either the drag reduction technology or the fuel consumption reduction technology could use these studies as a grounds for comparison. For example, take the particular technologies under consideration as follows: 1) 15% drag reduction ($kcdof = 0.85$) achievable with a 5% airframe cost increase ($kCaf = 1.05$), and 2) a 10% fuel consumption reduction ($kbsfc = 0.9$) achievable with a 12% increase in engine cost ($kCeng = 1.12$). Both of these hypothetical technologies result in an estimated demand increase of 5%, and thus the two technologies have the same relative benefit. Now, if a technology that reduces fuel flow by 5% ($kbsfc = 0.9$) and increases engine cost by 4% ($kCeng = 1.04$) is introduced, it can be evaluated as the best choice, with a positive demand impact of 7%.

Next, the effects of a cost penalty are studied on the E2F implementation. An E2F system could potentially be very expensive, but if it can allow a large increase in pilots, it may still be acceptable. Figure 99 displays demand contours with variation on the avionics cost (y-axis), as a fraction of the reference aircraft acquisition cost, and design speed (x-axis), with E2F implemented.

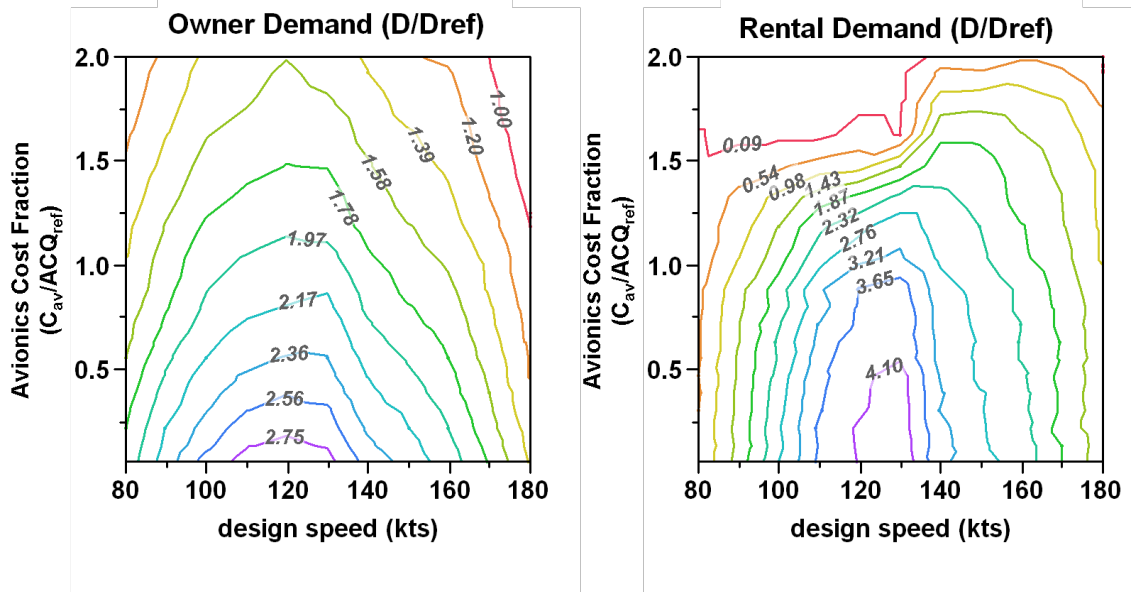


Figure 99: Owner and rental demand contours with sensitivity to E2F cost.

As one expects, the benefit of E2F declines as the cost increases. But, while owner

demand immediately declines, rental demand is initially invariant. Here, as both markets lose demand due to rising cost, some of the demand lost from the owner market migrates to the rental service. The rental service provider must buy the aircraft but also requires significant non-aircraft related costs (e.g. employees, office space), which softens the impact of the aircraft cost on the rental rate handed down to the consumer. After this demand plateau is passed, the rental market quickly dissolves, as the avionics system cost makes operation non-viable. The owner market continues to decline, but at a lower rate, as the choice of ownership is made on an individual basis.

Examining the trends of design speed for maximum demand indicates what aircraft is best suited for E2F. As the cost increases, the plots indicate that the most beneficial aircraft speed also increases, especially for the rental market. The rising cost translates to higher paying customers, and thus the door to door time becomes increasingly important.

7.3.2 GAP: Driver and Disruptor Scenarios

The technology implementation scenarios, as seen in the previous sections, demonstrated the effects of directly impacting potentially controllable systems, such as the aircraft. The GA transportation system can also be affected by *drivers* and *disruptors* that have indirect, yet significant impact. Drivers typically refer to the impacts by stakeholders which can have potentially positive effects - e.g. the general increase of the populations' wealth, or the societal acceptance of a new idea or way of life. Disruptors typically refer to negative impacts - e.g. bad weather or restrictive policies - that decrease the effectiveness of the system. A set of practical driver and disruptor scenarios, which have an implied positive or negative effect, respectively, have been developed for study, and are described in Table 33.

Table 33: Driver and disruptor scenario analyses.

Scenario	Description	Modeling
Baseline	Representative of current day socioeconomic distributions, travel demand, and network resources.	Calibrated model, see Implementation.
High Income	Consumers' incomes increase relative to the cost of travel.	Agents' income distribution multiplied by factor of 25%.
Severe Airline Delays	Air traffic congestion and increasing door-to-gate complications.	Mode airline (ALN) travel time increased by one hour for all trips.
Cheap Jet Taxi	Jet taxi networks become widespread and affordable.	Per seat price of mode jet taxi (GAJ) is decreased by 25%.
Rising Fuel Price	The price of fuel continues to rise, doubling in price.	Per gallon price of GAP fuel is increased by 100%.

These scenarios are perturbations from the baseline conditions, which a designing entity may wish to anticipate, and understand how the magnitude of demand would be affected, as well as how the best design settings might be affected. Thus, under each scenario, the design speed is varied, and changes in optimal speed for each market tracked. The market demands have been collected for each scenario, and are plotted in Figure 100.

These results show that such scenarios can have large impacts on the GA transportation system, in some cases as much, or more, as the technology implementation simulations of the previous sections. From market to market, it is apparent that the service markets are more susceptible to these scenarios, sometimes in a positive way, as with scenario 'High Income', and sometimes in a negative way, as in scenario 'Rising Fuel Price'. The service markets rely on an additional element in the balance of supply and demand, namely the service provider, for which the fragility of their viability is apparent here. Also, the rental and taxi consumers decisions are made on a trip by trip basis, and thus can easily be swayed to and from its usage. On the other hand, owners require a large investment in acquiring the aircraft, and become a part of the market only after considering the long term usefulness of the aircraft. This decision is less likely to be swayed, as the long term, large investment considerations carry considerable inertia.

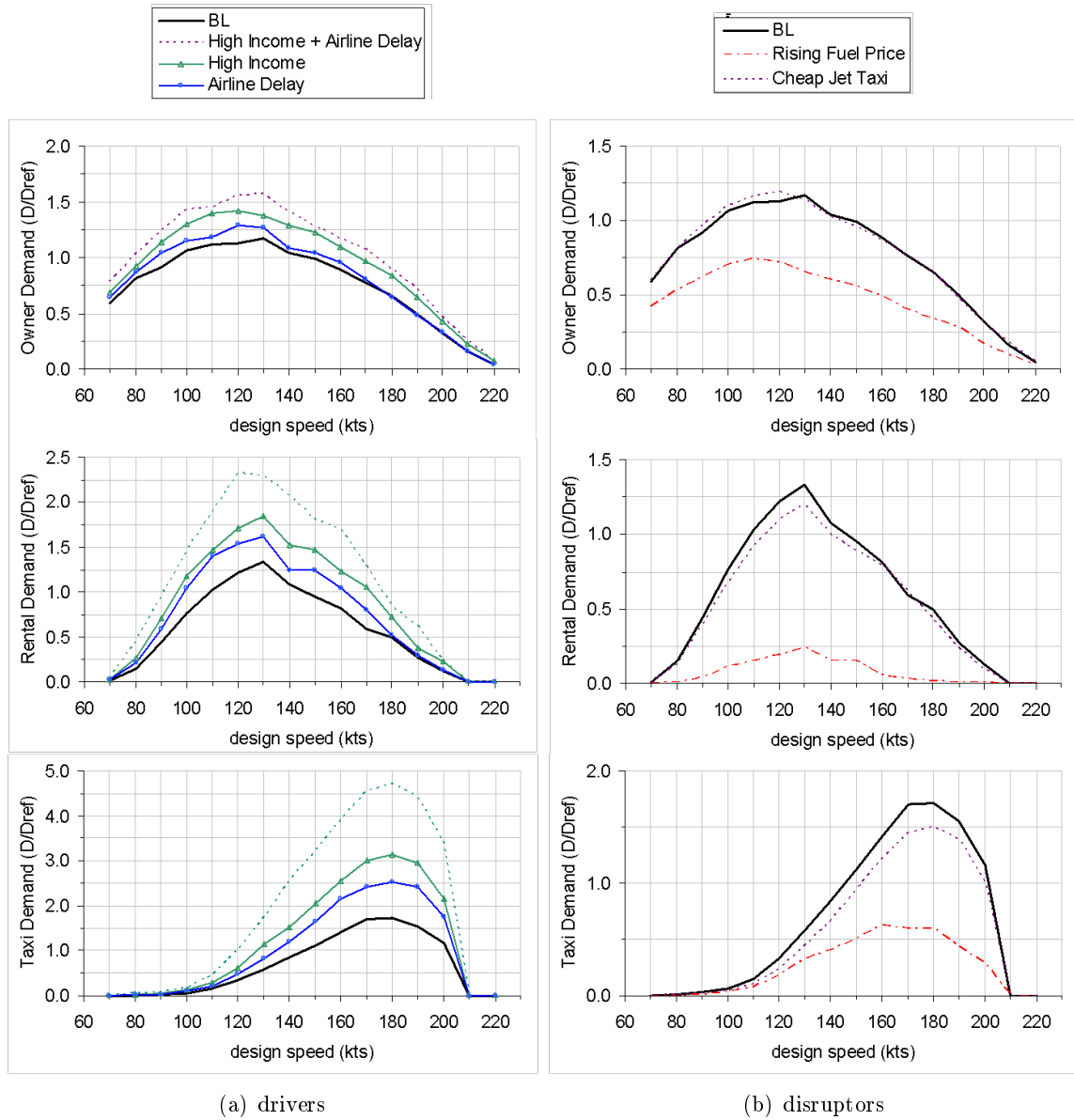


Figure 100: GAP driver and disruptor scenario results.

Beginning with the disruptors, scenario 'Rising Fuel Price' has very strong negative impacts on all the GAP markets, but especially the service markets, which are essentially squandered. This additional cost raises the operating costs of the service provider, detrimen-ting their viability, and of course trickles down to the consumer, making the service less attractive. Also note that this scenario tends to shift the optimal design towards a slower aircraft, likely more fuel efficient.

Scenario 'Cheap Jet Taxi' mostly effects the taxi market, and then the negative impact is small. This implies a considerable difference in the consumer base between these similar markets, as they are not quick to change, even with a substantial cost decrease.

Moving on to the drivers, scenario 'High Income' has the greatest positive effect on all markets, especially the taxi market, which sees a doubling of maximum demand. This is expected, because the population of pilots, a requirement for the rental and taxi markets is relatively small in comparison to the population of those who can use the taxi service, which is essentially the entire population.

Scenario 'Airline Delay' also has a fairly large impact, especially on the taxi market. The combination of the driver scenarios induces greater impacts to the service markets than the independent additive effects of either scenario alone.

7.3.3 GAP: Multi-System Design

In this section, the design aspect is expanded to the service provider. The service provider has control of many factors pertaining to how they define their operation. In theory, they have full control of these factors, but in reality, a combination of market forces will influence their decision. For example, any rental rate can be set, but the service provider's ultimate goal is to find the rate that allows a balance of satisfactory profit and stability, generally achieved by increasing demand volume. As will be seen, these metrics do not necessarily go hand in hand, and tradeoffs can be required. How they choose to make these tradeoffs can also impact how they compose their primary resource, their aircraft fleet, in terms of the size of the fleet and the aircraft characteristics. This section strives to demonstrate how these interactions can be assessed in the conceptual design phase.

Two variables are defined for the service provider: rental price mark up, $pMarkup$, and fleet loading, fl . As defined by Equation 32, the fleet loading, determines the size of a local service provider's fleet as $Q_j = \frac{D_{j,avg}}{fl}$, where Q_j and D_j are the fleet size and the average weekly expected demand, in trips, at service provider location j , respectively. Essentially it indicates the ratio of expected demand per week to the number of aircraft in the fleet. Higher values indicate a smaller fleet, and will tend to result in aircraft shortages, and lower values indicate a larger fleet and will tend to result in greater ownership expenses. The rental price mark-up determines the hourly rental price, p , paid by the rental consumer as a scalar of the direct operating cost, DOC , i.e. $p = pMarkup \cdot DOC$. For each hour of flight time, the rental consumer pays p dollars and the taxi consumer pays $p + p_{pilot}$, where the pilot hourly surcharge is \$350³. A “design space” grid is defined in Table 34.

Table 34: Service provider “design space” definition.

variable	min	max	step	baseline	unit
$pMarkup$	1.2	2.8	0.2	1.8	
fl	1	3	0.5	2	trips/AC/week

For starters, the individual impacts of these variables are studied. Unless noted, the GAP aircraft design variables are held at the baseline values. Figure 101 shows the results for variation of fleet loading, where the demand and profit metrics pertaining to the service provider have been calculated. The bifurcation of peaks between the profit and demand metrics is explained further. Although demand is lost at the higher fleet loading, where profit maximization occurs, the service providers' fleets are smaller and thus their expenditures are less. In reality, this may have a negative impact on the demand, as customers will be turned away more often, which may inhibit their future usage of the service. Additionally, if competition is a factor, another service provider can be more attractive to the consumers by decreasing their fleet loading, such that their customers are rarely turned away. In this example, choosing the point of maximum demand comes with a trade of approximately 12%

³Determined from SATSair taxi rate (\$600/hr), and corresponding average aircraft rental (\$250/hr).

loss in profit.

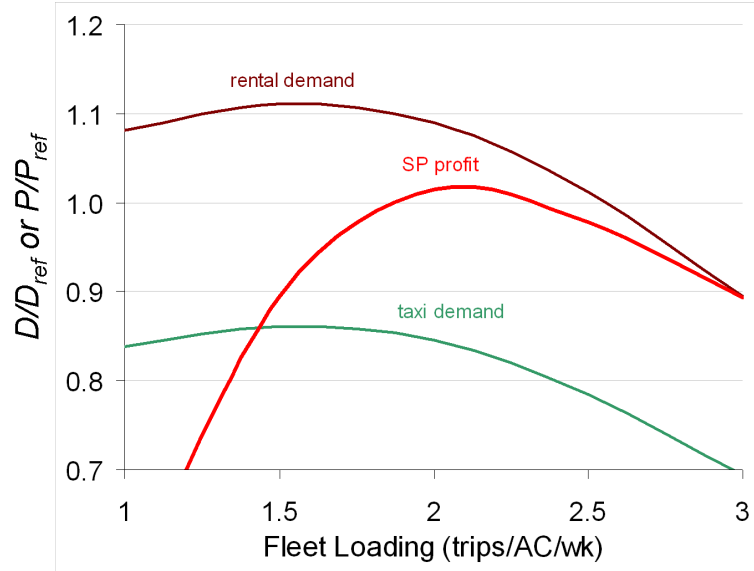


Figure 101: SP-centric analysis: Demand or Profit v. Fleet Loading.

The independent effects of varying the price mark up are displayed in Figure 102. Here again, the profit and demand metrics occur at different variable values, and this time the difference is significantly greater. Profit is the product of demand and the specific profit gained by each unit of demand, thus the point of maximization occurs when the rate of specific profit of lost customers equals the specific profit gained from retained customers. Again, with competition, choosing this point of operation may be unstable. Although theoretically they can adjust their mark up at any time, they may not want to make long term decisions, such as choosing the fleet size, under this assumption. The point of maximum demand results in almost 50% decrease in profit, so a compromise solution may be most suitable.

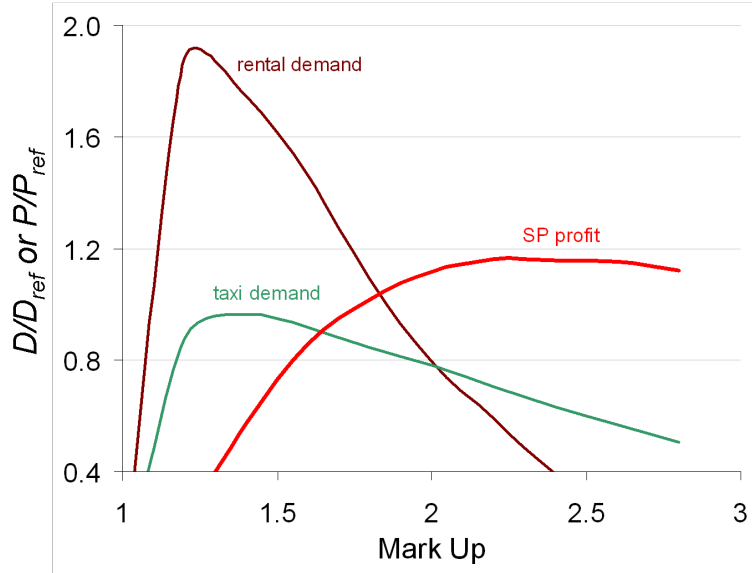


Figure 102: SP-centric analysis: Demand or Profit v. Mark Up.

In the decision making process, the most informed decision is desired. The above studies have demonstrated some key trends, but the simultaneous interaction of the variable effects, as well as the effects of the aircraft design will be more informative. Thus a full factorial grid analysis, with dimensions of fleet loading, mark up, and design speed, is performed, and the results are displayed in Figure 103. In this multi-variate plot, a large amount of information is available, namely the mappings of all combinations of the independent variables and a number of selected metrics. The independent variable labels at the bottom of the far right three columns indicate the dimension of the x-axis of the corresponding column. The metric labels along the diagonal on the left side of the plot indicate the dimension of the x-axis and y-axis of the corresponding column and row, respectively. Plots below the diagonal would be transposes of those above, and thus are removed for clarity.

The demand and profit metrics are included, as well as the rental rate, an intermediate metric, which is a function of the direct operating cost and the mark up. As seen before, the demand and profit metrics all peak at distinct values for each one of the independent variables. The separation of the peaks from metric to metric is most pronounced with the mark up and design speed variables, and the fleet loading now shows that all metrics tend towards a value of two. These effects translate to tradeoffs which are further pronounced

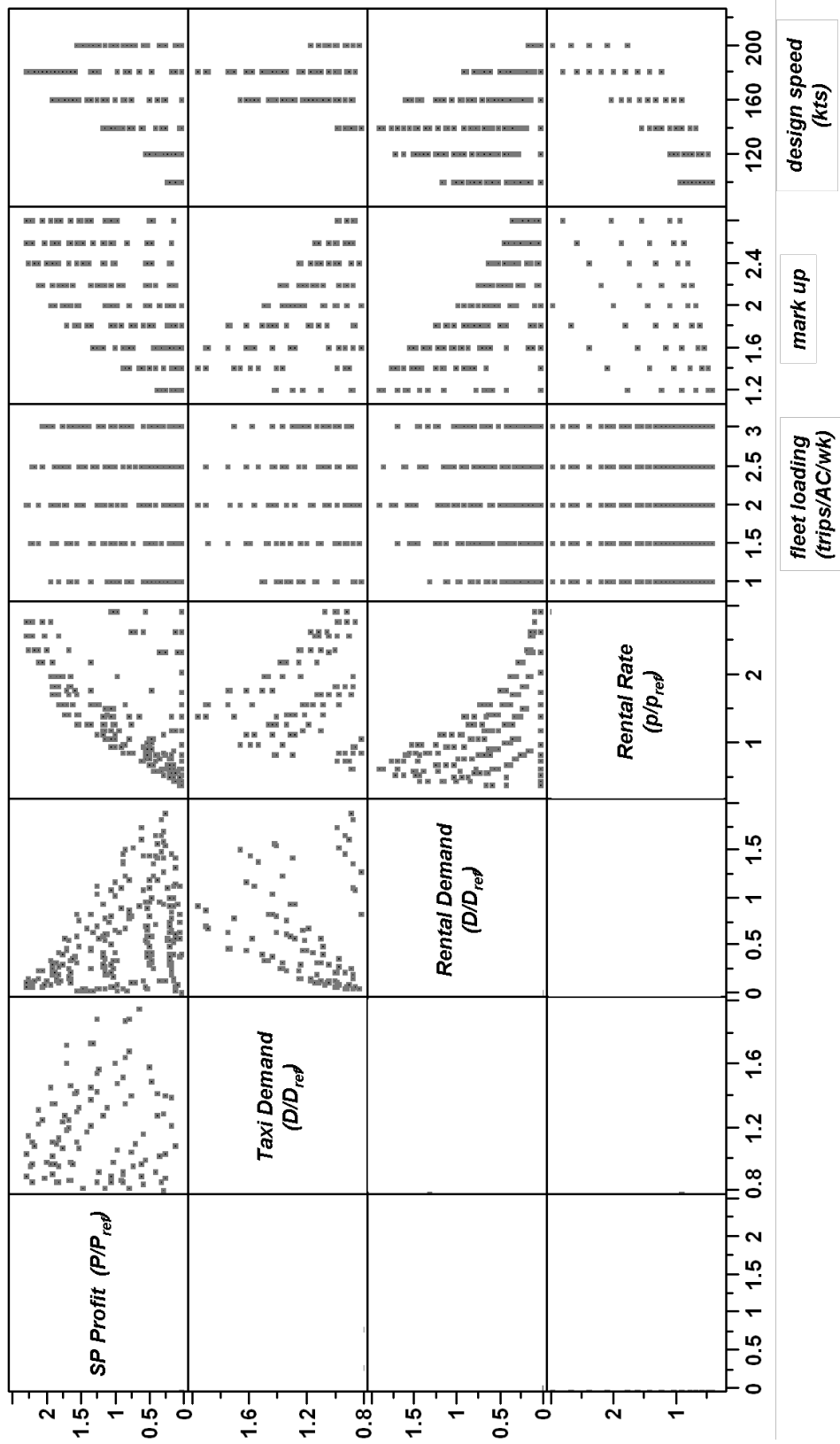


Figure 103: GAP multi-system design space.

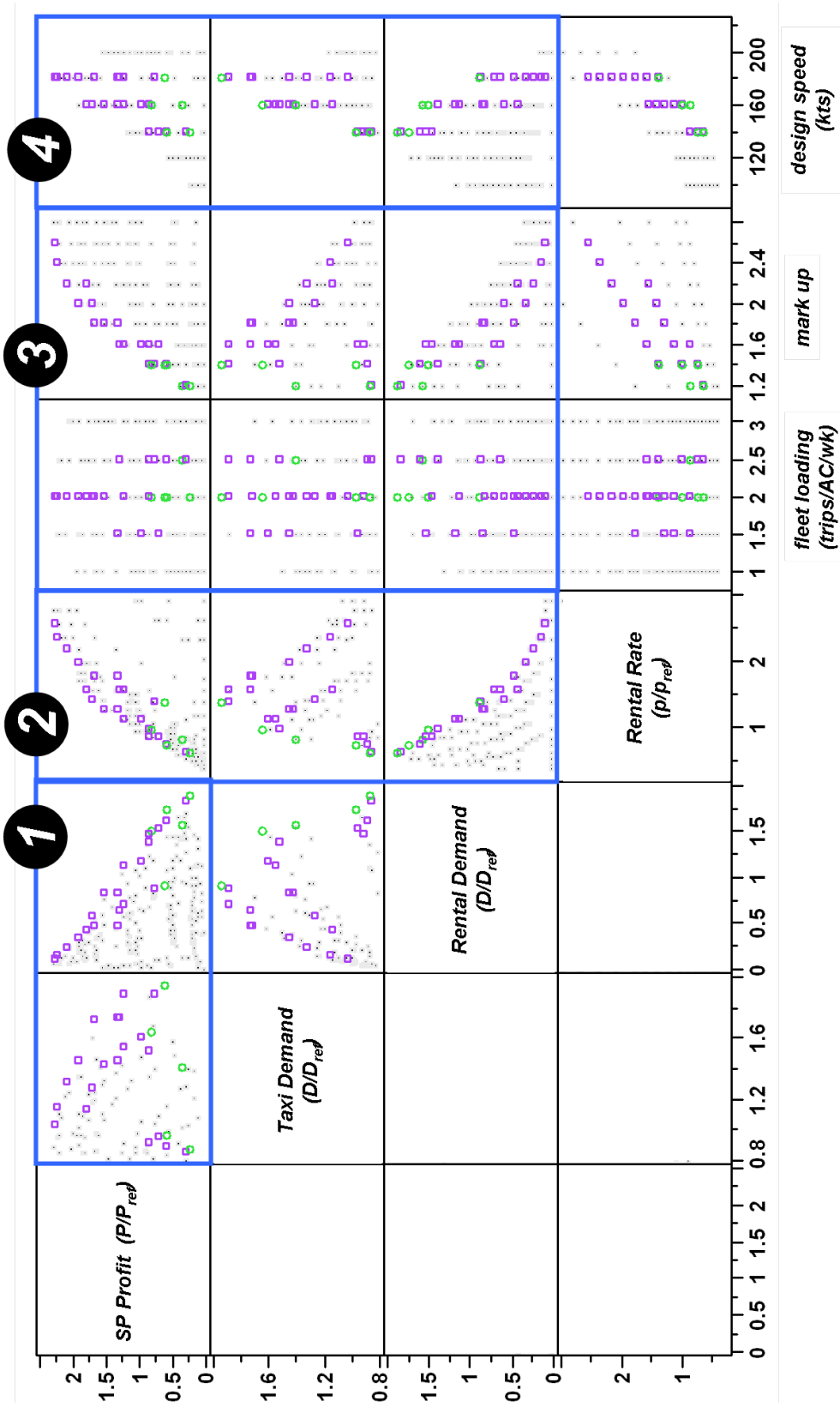


Figure 104: GAP multi-system design space, Pareto filtered.

when observing the metric space plots. Before proceeding, some filtering is performed to clarify the results. All results are filtered for Pareto optimality in relation to demand and profit metrics.

In Figure 104, the purple squares indicate those that are Pareto optimal for all demand and profit metrics, and the green circles indicate those that are Pareto optimal for only the demand metrics, respectively. These points are likely of greatest interest to a decision maker, and by default will include the single objective optima of each individual metric.

Figure 104 also includes a number of labeled boxes, each of which provide different perspectives of the results. Box 1 contains the metric trade spaces, where the tradeoff among metrics become clear. Tracking the demand only Pareto optimal points, in green, up to the profit-demand plots shows that they translate to the lowest profit levels, emphasizing this tradeoff dilemma.

Moving to box 3, where the metrics are mapped to the service provider control variables, the primary cause of the profit-demand trade becomes apparent. The Pareto optimal points clearly tend to increase in profit as mark up increases for the profit metric, and in opposition decrease in demand. Additionally, all of the green, demand Pareto optimal points have low mark up values (1.2-1.4). One can also see in box 4, where metrics are mapped to the aircraft design variables, that the metrics are influenced by the design speed, albeit with considerably less correlation. Here the taxi demand and profit both increase with speed, up to 180 kts, where as the opposite is true for the rental demand. This indicates that the taxi-rental demand tradeoff, clearly seen in the plot of taxi demand against rental demand in box 1, is driven by the design speed variation, rather than the service providers control variables.

Consider a situation where the service provider has the choice between maximization of profit and maximization of rental demand. Maximization of profit is desirable from the economical sense, but opens the possibility for entrance by competitors offering a lower ticket price and settling for lower profits. Maximization of demand makes the consumers happy, and may provide a level of stability - having a larger customer base - while discouraging competition. According to the results, if maximization of profit is chosen, the service

provider will choose a mark up of 2.6, and a fleet of 180 kts aircraft. On the other hand, if maximization of demand is chosen, a mark up of 1.2 and a fleet of 140 kts aircraft will be selected. Here, the choice of how the service provider operates has an effect on which aircraft design is most desirable.

Finally, box 2 plots the demand and profit metrics against the intermediate metric, the rental rate. Here a vast difference is seen in the rental rates that result in optimality for each of the three high level metrics.

A simplified viewpoint of these results is displayed in Figure 105, where only a select number of points have been kept, and the metrics have been reduced to the rental demand and profit. Each curve represents a variation of aircraft speed (generally increasing clockwise around the curve) at a constant mark up.

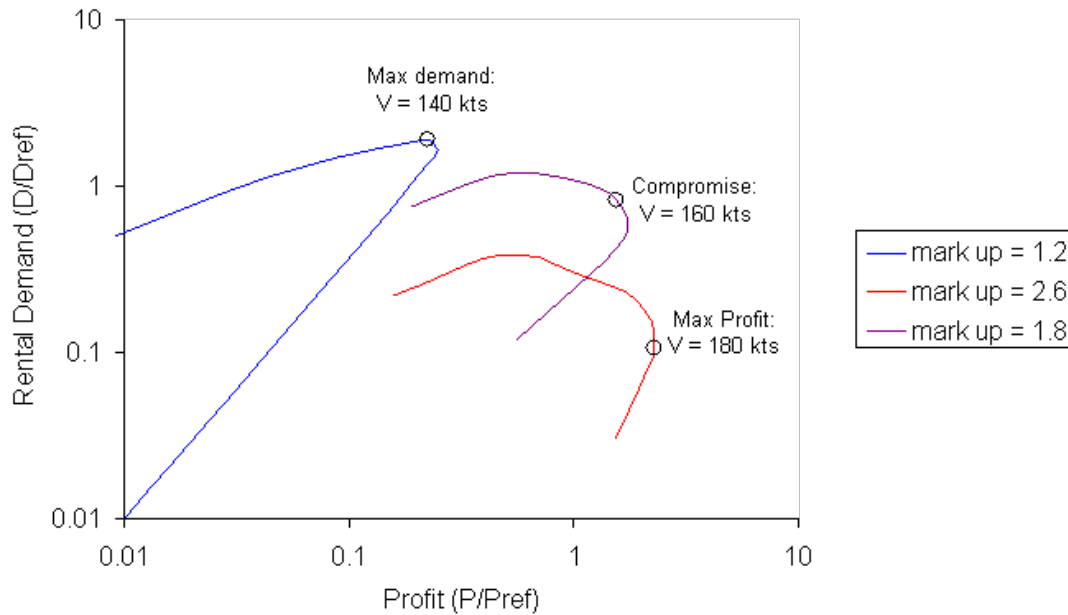


Figure 105: GAP multi-system design space - tradeoff exemplification.

Under a hypothetical scenario where a service provider has the ability to freely choose between profits and demand volume, a tradeoff must be made. This was seen previously in box 1, Figure 104 as a Pareto frontier and is seen again in Figure 105, although now with some points removed for clarity. Three remaining points which lie on the frontier have been

labeled as max demand, compromise, and max profit, and are characteristic of this tradeoff. What is interesting to note is that achieving each of these points comes with a different combination of design speed and mark up. This implies that a cooperation between the service provider and the manufacturer could produce greater results, i.e. a synergy, where independently derived solutions may lead to a solution that does not lie on the Pareto frontier.

7.3.4 GAP: General Analysis Methods

Although emphasis has been on the analysis of captured demand, the analysis environment naturally has hundreds of metrics available for study on various levels. In the presented studies, reduced sets of metrics have been chosen to concisely represent various entities in the GA transportation system, but in general, one may wish to explore a greater variety of metrics, and their interactions, in further expanded multi-system analysis. Here, a generalized treatment of the design trade spaces is given as a guide for further exploration.

In Figure 106, an example multi-variate plot is presented, including 15 representative independent variables, intermediate metrics, and high-level metrics. A multi-variate plot allows the simultaneous assessment of many variables and metrics by displaying a matrix of plots, where each block of the diagonal indicates the variable or metric that is on the x-axis of every plot block of that column, and on the y-axis of every plot block of the row.

The metrics and variables are distinguished by three levels: independent variables, intermediate metrics, and high-level metrics, as indicated on the far left. High-level decision metrics, such as captured demand and profits, are metrics by which the decision maker would ultimately want to make design decisions. Intermediate metrics are system or specific metrics, e.g. cost and performance metrics for the aircraft designer. These metrics are a function of the independent system design variables and are also drivers for high-level metrics. The independent variables describe the design or requirements imposed on the respective systems, e.g. design speed.

The trade spaces defined by the interactions of these variable types are categorized by the colored sub-blocks, and the nature of each is described. The blue sub-block is the high-level

trade space. This is the new tradeoff space⁴, where the interactive nature of high-level metrics is observed, in both intra-entity and inter-entity manners. Intra-entity trades are addressable by the corresponding entity's decision makers, whereas inter-entity tradeoffs in general can only provide one entity an understanding of how to collaborate, or prepare for action of another entity.

The yellow sub-block corresponds to the traditional metric trade space, e.g. the aircraft cost-performance trade space. These metrics have now become intermediaries in the process, and are no longer the final source for decision making, but they provide useful insight into the nature of the solutions at hand, e.g. what acquisition cost and engine horsepower corresponds to maximum demand.

The purple sub-block is the mapping of the high level metrics to the independent variables, e.g. the demand to design requirement mapping. Here the total effect of independent design changes on high-level metrics is indicated. This indicates what design settings will ultimately provide the best results, given a decision metric, e.g. captured demand.

The green sub-block contains the mappings of the intermediate metrics to the high-level metrics; a space addressing what system targets are required to produce the best high-level results, e.g. what is the acquisition cost corresponds to maximum demand.

The orange sub-block indicates the mappings from the independent variables to the intermediate system specific metrics, and represent the system analysis modules. The pink sub-block is simply the independent variables, which should have no interaction, here showing the gridded full-factorial input. In a multi-variate optimization problem, this space will indicate the correlation of optimal independent variables.

A completely different type of analysis, likely to be performed after analysis of metric and variable mappings, is the viability mapping. Viability mapping, which is the spatial mapping of viable service provider locations, as determined by the modeling environment, can be a potential benefit when making design decisions. Figure 107 displays a viability map for each of the four technology scenarios. Each circle on the map represents a potential

⁴In reference to the aircraft system level metric trade space, i.e. the performance-cost trade space, of traditional design methods.

market population, in this case a county, where the area of the circle is proportional to the population. Each population that has been found as viable is colored blue, and each found as non-viable is colored red.

This type of analysis can be used to determine regions of dense demand, where a localized operation might be most suitable, and further in addressing network aspects, e.g. route planning. Although the latter is beyond the scope of this research, visualization of such results provide additional means for designers and decision makers alike to understand, make sense of, and monitor the results of the modeling environment.

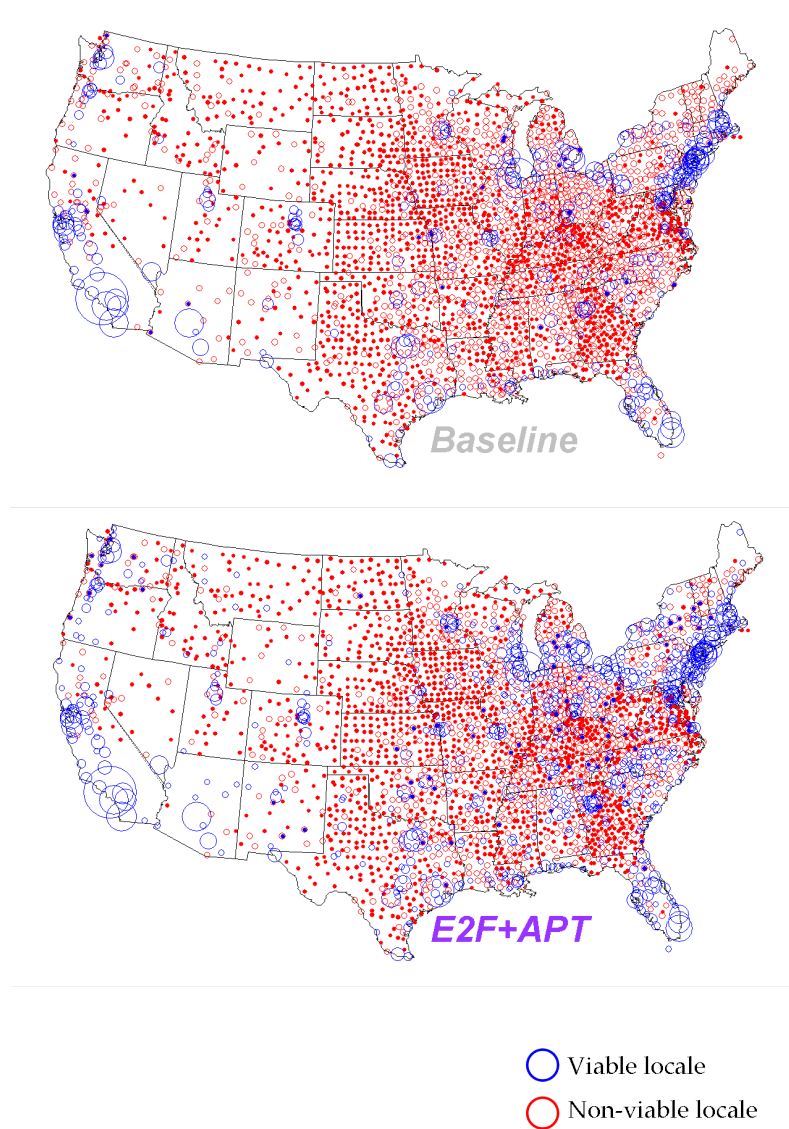


Figure 107: Rental viability mappings.

7.3.5 GAJ: Baseline Design Space

In a similar fashion as the GAP, the GAJ is parametrically studied. As before, the design space is represented by a full-factorial grid of design variables, defined by the bounds and discretization indicated in Table 35. Prominent assumptions that have been made include an annual useful utilization, U_{sp} , of 750 hrs, required service provider and manufacturer return on investment of 15%, and the “deadhead” fraction, f_{DH} of 30%. These values correspond to the calculation of GAJ ticket price viability, summarized by Equation 38.

Table 35: GAJ aircraft design space definition.

variable	min	max	step	unit
Mach	0.4	0.8	0.1	Mach
payload	3	8	1	pax
range	600	1600	250	nm

The baseline results are plotted as metric to requirement mappings, this time in 2-d contours, displayed in 108. Additional metrics, the service provider profit (P , $P_{ref} = \$148\text{M}$) and required fleet size (Q , $Q_{ref} = 621$ units), are included to analyze the effect that design has on high-level decision making. These metrics have been chosen to represent the desirability of each of the three important entities: consumers (demand), service provider (profit), and manufacturer (fleet size). In the plots, the range is held constant at 850 nm. This clarifies analysis of the results, and little effect is lost as this value was found to be optimum for all relevant configurations.

Beginning with the demand, it is seen that rather than forming a distinct peak, it plateaus in relation to the payload, 5-6 pax, and speed, 0.6-0.7 Mach, requirements. In relation to payload, as the number of seats grows, the size and cost of the aircraft increase, but at the same time the cost is spread among a greater number of travelers on a given flight, which reduces the ticket price. Additionally, the on-demand penalty decreases the utility of the service as the number of seats grows. Similarly, the speed requirement experiences a cost-desirability trade, which the consumers, service providers, and manufacturers influence,

and are revealed by the metric trends.

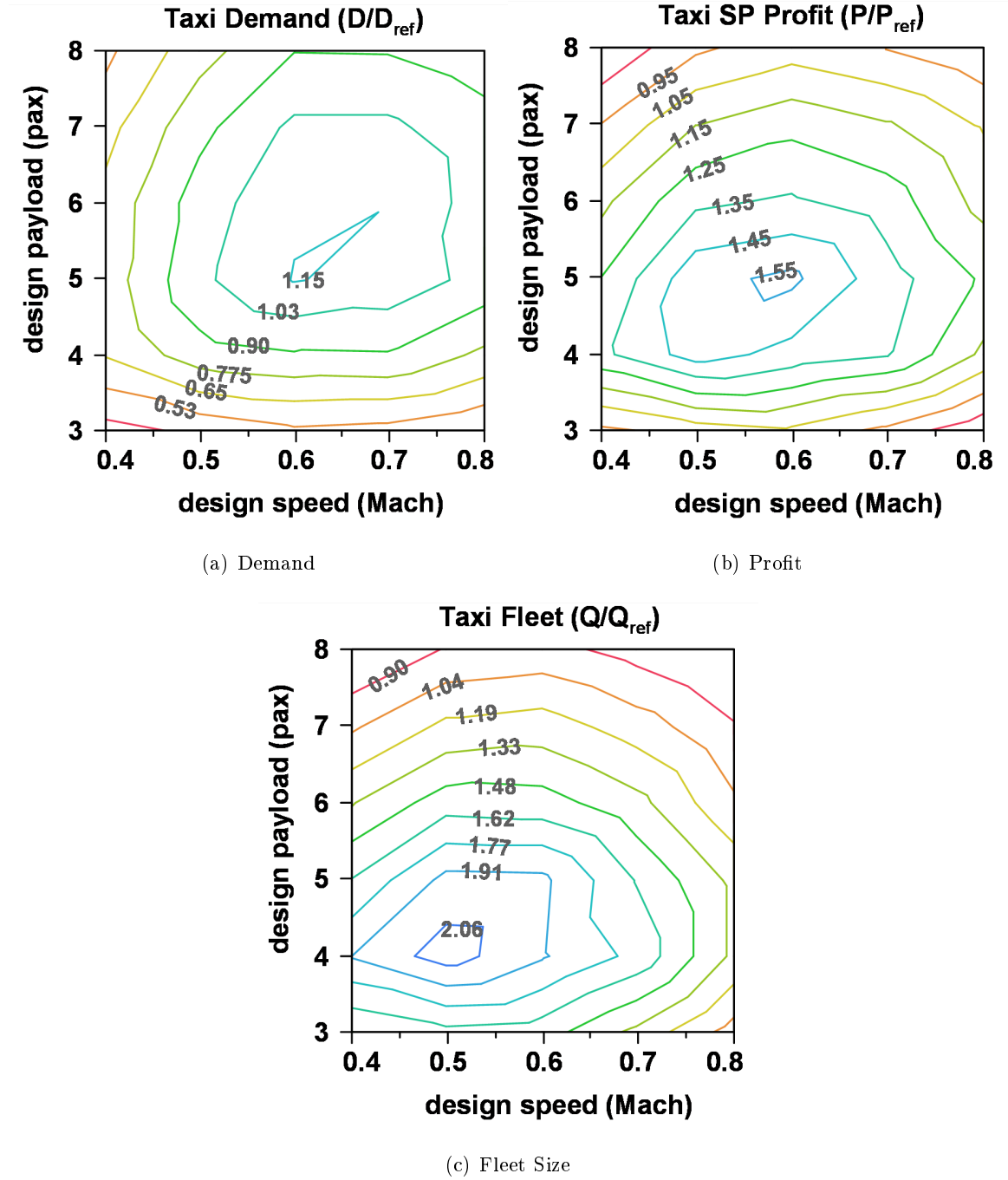


Figure 108: GAJ baseline design space metric contours (range = 850 nm).

Additionally, an interesting correlation is seen between the two requirements, i.e. the demand plateau goes from {5 pax, 0.6 Mach} to {6 pax, 0.7 Mach}. This implies that the consumers are equally willing to take an on-demand penalty, i.e. add a seat, if the aircraft

speed also increases.

Moving on to the service provider's profit metric, they will prefer to operate at 5 pax and 0.6 Mach for profit maximization. Although the maximum demand is actually achieved at {6 pax, 0.7 Mach}, the change is relatively small over the indicated plateau, and an operation can exist where both the consumer and service provider can be mutually satisfied, and the metrics can be considered synergistic. One might intuitively assume that maximization of demand and profit go hand in hand; profit is the product of passenger trip demand and the specific profit for each passenger trip, thus this is not necessarily the case. For example, one customer, who prefers a high level of on-demand service, may pay \$500 for a single trip, which incurs a service provider expenditure of \$200, this will result in a greater profit than two passengers paying \$200 a piece, at the same expenditure.

The size of the required fleet, Q , grows with demand, as more passengers need to be moved, and it is also directly affected by the payload and speed of the aircraft. The fleet required to carry a fixed number of passenger trips increases as the payload capacity and speed decrease. As the size of the fleet grows, the aircraft cost can also be affected ($ACQ\ 1/Q$), which aids the viability of the service provider and can trickle down to the traveler as a cheaper ticket.

Additionally, a 4-node neural network has been created using the design grid results, and the prediction profiler is shown in Figure 109. The prediction profiler indicates the change in responses or metrics (y-axes) along orthogonal slices passing through a selected input point (x-axes). In other words, each plot shows the variation from a reference point, indicated here by the red hairlines, along each dimension of the design space while keeping all other variables constant. While this tool provides limited usefulness in a static context, it is a very useful tool when actively "surfing" a high dimension design space.

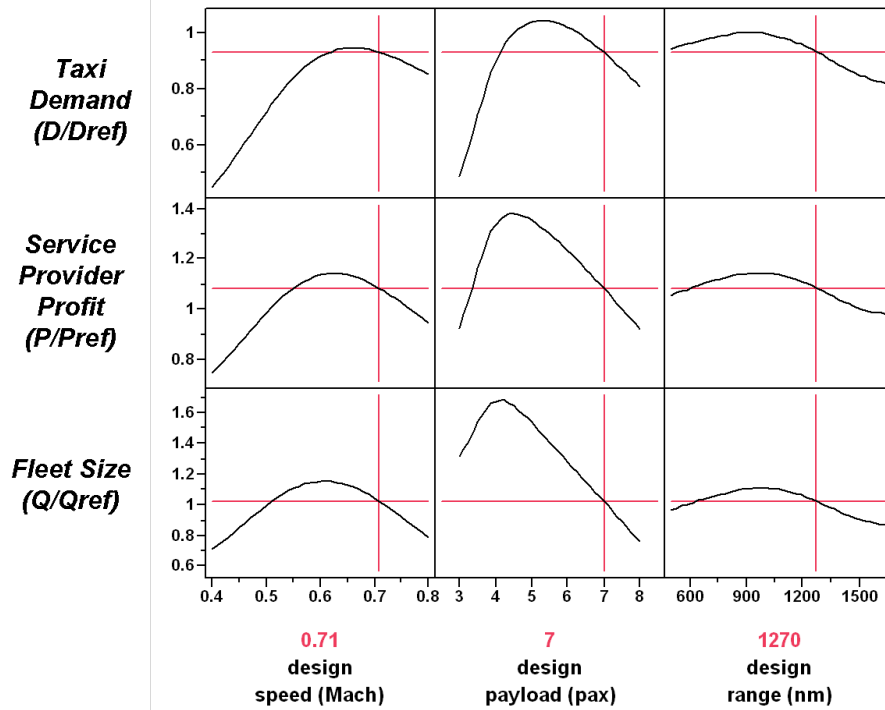


Figure 109: GAJ air taxi prediction profiler.

Having the trends of the baseline GAJ design space established, some investigations of current interest are addressed. Unlike the GAP studies which focused on technology based scenarios, this GAJ studies focus on driver and disruptor scenarios. These types of scenarios involve effects from entities that are not a direct part of the system of interest, are likely affected by unrelated events and conditions, but still have significant impact.

7.3.6 GAJ: Fuel Cost Sensitivity

As this paper is being written, the price of oil is passing values never seen, and continues to rise. This is undoubtedly a concern for business jet operators, as the aircraft are notorious “gas guzzlers”, as demonstrated by a notional comparison of aircraft fuel consumption in Figure 110. It is clear that jet aircraft require very large passenger capacity before the fuel consumption per passenger becomes comparable to piston or even turboprop aircraft. In the GAP study, a doubling of fuel price was seen to squander all service providers’ chances of viability. Thus, the analysis environment is utilized to estimate the impacts that varying

fuel cost might have on the taxi operation.

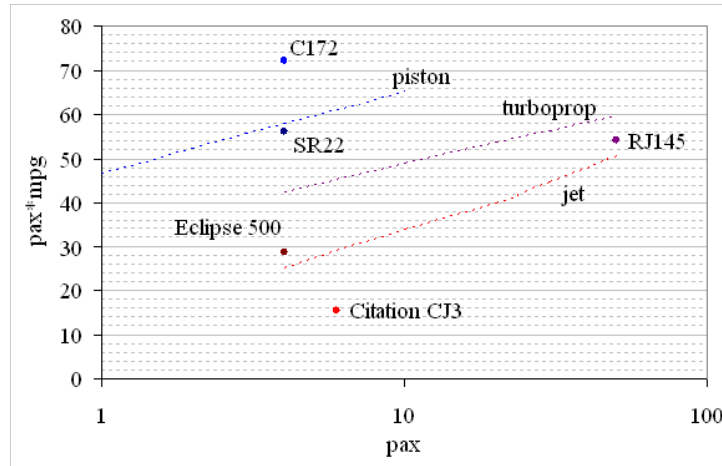


Figure 110: Comparison fuel consumption by aircraft type.

In this study, the cost of fuel is varied from \$3-\$6 per gallon. For each setting, the design payload is varied across the original design space range. The design range and speed, which are less influential, are held constant at 850 nm and 0.6 Mach, respectively. The taxi demand and service provider profit are tracked, and the results are displayed in Figure 111.

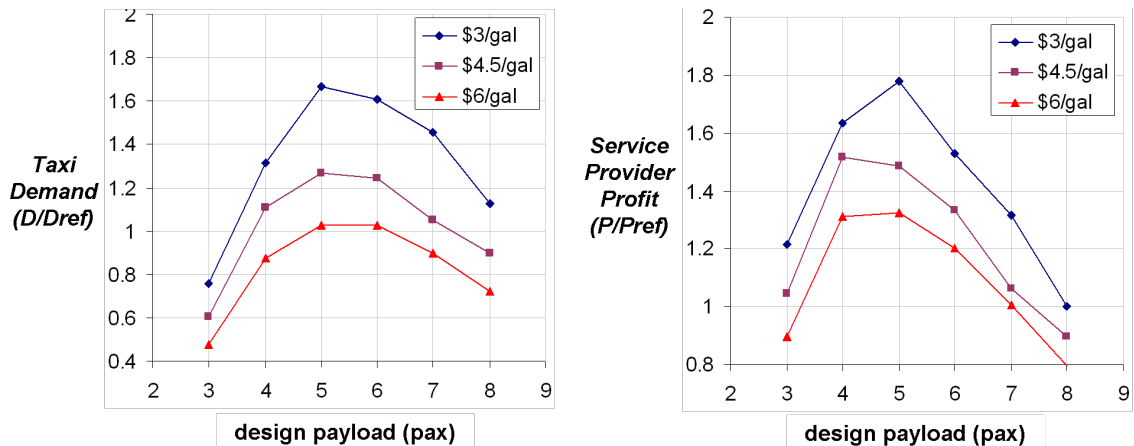


Figure 111: GAJ fuel cost study results.

The effect on demand volume is clearly detrimental, declining an average of 20% for every \$1.50 rise in fuel cost. Also apparent is a shift in the optimal design payload. Interestingly, rising fuel cost shifts the optimal design payload to a *higher* value with respect to demand,

while shifting it to a *lower* value when profits are concerned.

Conceptually, demand represents the satisfaction of the consumer population, as the greater demand captured, the greater the number of consumers satisfied. On the other hand, profit represents the satisfaction of the service provider, who regardless of demand volume is making more money. In this case, it is seen that the majority of consumers prefer a shift to greater design payload, as this allows the increasing fuel cost to be distributed among other customers. The service provider prefers a shift to a lower design payload, because although demand declines, it is the product of specific profit, that is profit per passenger, and demand that determines the total profit. Apparently the specific profit of customers preferring improved on-demand service over a lower ticket price drives the design for maximum profit to a 4 pax configuration.

7.3.7 GAJ and GAP Air Taxi Interactions

Another topic of interest is the interaction of the GAP and GAJ taxi markets. Previously, the GAP design speed and the GAJ payload were seen to be highly influential variables for the GAP and GAJ, respectively. Thus, these variables are parametrically varied, analyzed, results gathered and plotted in Figure 112. The contour plots indicate the demand of each market, with respect to the two variables.

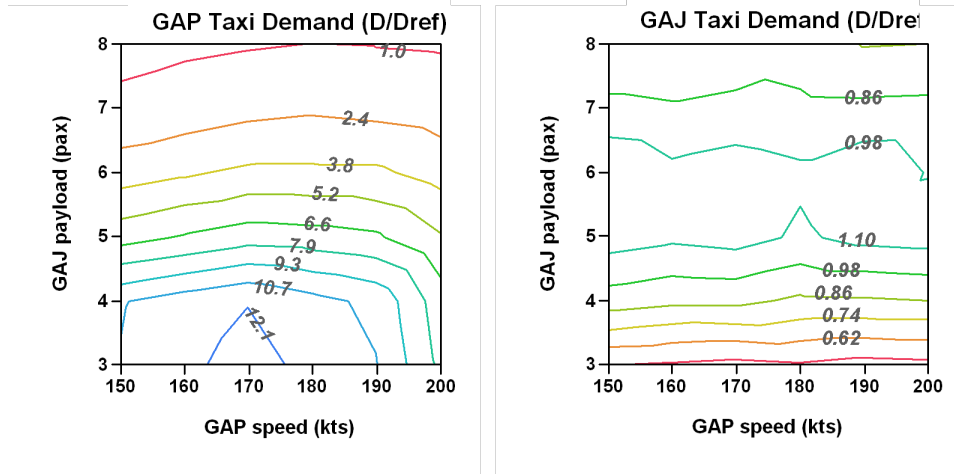


Figure 112: GAJ-GAP interaction study results.

Corresponding to previous results, the GAP and GAJ variables display demand peaks

for their respective markets, but now interactive influences are also apparent. The GAP speed has no discernible effect on the demand for GAJ taxi, but the GAJ payload shows a strong interaction. This interaction is seen as a decline in GAP taxi demand as the payload increases, with a very steep gradient. What appears to be occurring is that as the seating capacity of the GAJ increases, the ticket price decreases, and the on-demand penalty increases, making the GAJ service very similar to the GAP taxi service.

In reality, this interaction may not be as strong, because GAP taxi has a much higher level of on demand service, including absolute freedom when selecting the departure and destination airports, and essentially no waiting time at the airport. On the other hand, the GAJ taxi service has predetermined routes and schedules, albeit loosely established.

Also notable from the results is the continuing decline in GAP demand as GAJ payload increases, even as GAJ demand passes its peak around 6 pax. This result implies that the GAJ continues to attract GAP customers, but at the same time is losing a large number of customers who prefer a greater on-demand service, achieved with a lower payload aircraft.

Chapter VIII

CONCLUSIONS

The goal of this thesis has been to develop a conceptual design methodology that brings a more dynamic and objective perspective to the aircraft system engineer, through an environment that translates aircraft system design changes into architecture level decision metrics. To this end, a methodology was derived and implemented for study of a GA transportation system. This chapter first revisits the hypotheses throughout the thesis and attempts to determine how they have been supported by the work performed and what contributions arose during the process. Finally a list of suggestions for future work is presented.

8.1 Revisiting the Hypotheses

The statement of hypotheses throughout this thesis has been ordered such that each ensuing hypothesis helps to support the previous. Thus, the revisitation of hypotheses progresses in the reverse order in which they were stated. The modeling hypothesis posed an answer to the question of what system models need to be included in the system of systems model and its sub-hypotheses addressed what specific sub-models need to be developed and implemented in addition to the existing tools.

Throughout Chapters 4-6, the system models and sub-models addressed by the modeling sub-hypotheses were presented, including examination of sub-model behavior. This culminates in a list of component contributions that resulted as a process of pursuing higher level hypotheses. The component contributions are summarized as follows, with indication of the location in the thesis where it is discussed:

1. Development and implementation of weight and cost sub-models representing the GAP and GAJ fleets of today (Sections 4.1 and 4.2).
2. Development and implementation of utility-based ownership model adding the ownership decision on to the agent level; predicts the number of GA owners (Section 5.2)

3. Application of clustering methods for grouping nearby statistical populations into a common population for the purpose of defining service locations (Section 5.3.2).
4. Implementation of a county-level demand distribution model, utilizing local socioeconomic factors to estimate the production and attraction of GA travel demand (Section 5.3.2).
5. Development and implementation of a temporal demand distribution model representative of historical US GA travel demand (Section 5.3.3).
6. Re-characterization of demand prediction by the type of aircraft utilized (GAP, GAJ) and the type of operation (owner, rental, taxi), representative of current GA usage trends (Section C.2).
7. Implementation of the service provider fleet scheduling algorithm and development and implementation of parametric component cost models for total cash flow analysis of the GAP service provider (Section 6.1.2).

These contributions indicate the specific modeling contributions that were necessary to implement the system of systems methodology. These contributions were necessary, but the methodological contribution, presented next, is a culmination of the efforts in this thesis. First, the supporting methodological research hypothesis is revisited, which consists of several questions that should be addressable given that the methodology is successfully implemented. Each of these questions will be answered by presentation of the most relevant results found in the preceding chapter.

- Can optimal requirements – those that maximize “capability” – be resolved?
- If so, how do these requirements:
 - Differentiate between markets?
 - Evolve with technology improvements?

In Figure 113, a peak in demand is observed across a continuous variation of aircraft design speed, implying that this speed would be preferred, or optimal under the assumption that the viably captured demand is the best measure of capability. In addition, it is seen that this peak varies from market to market, and further that the peak shifts, with relation to design speed as technology is implemented. The ability to track the evolution of the preferred design speed was further understood through the APT strength study, displayed again in Figure 114. Additional answers to these questions might be interpreted from Figures 89, 97, 98, 99, and 33.

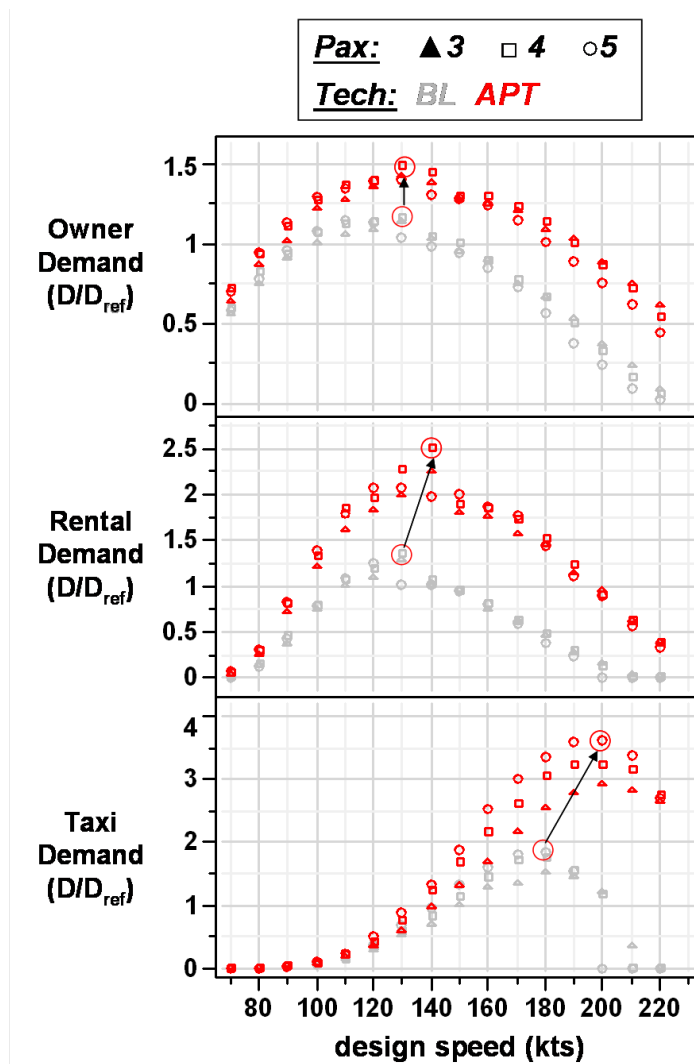


Figure 113: Normalized market demand: BL (gray) and APT (red).

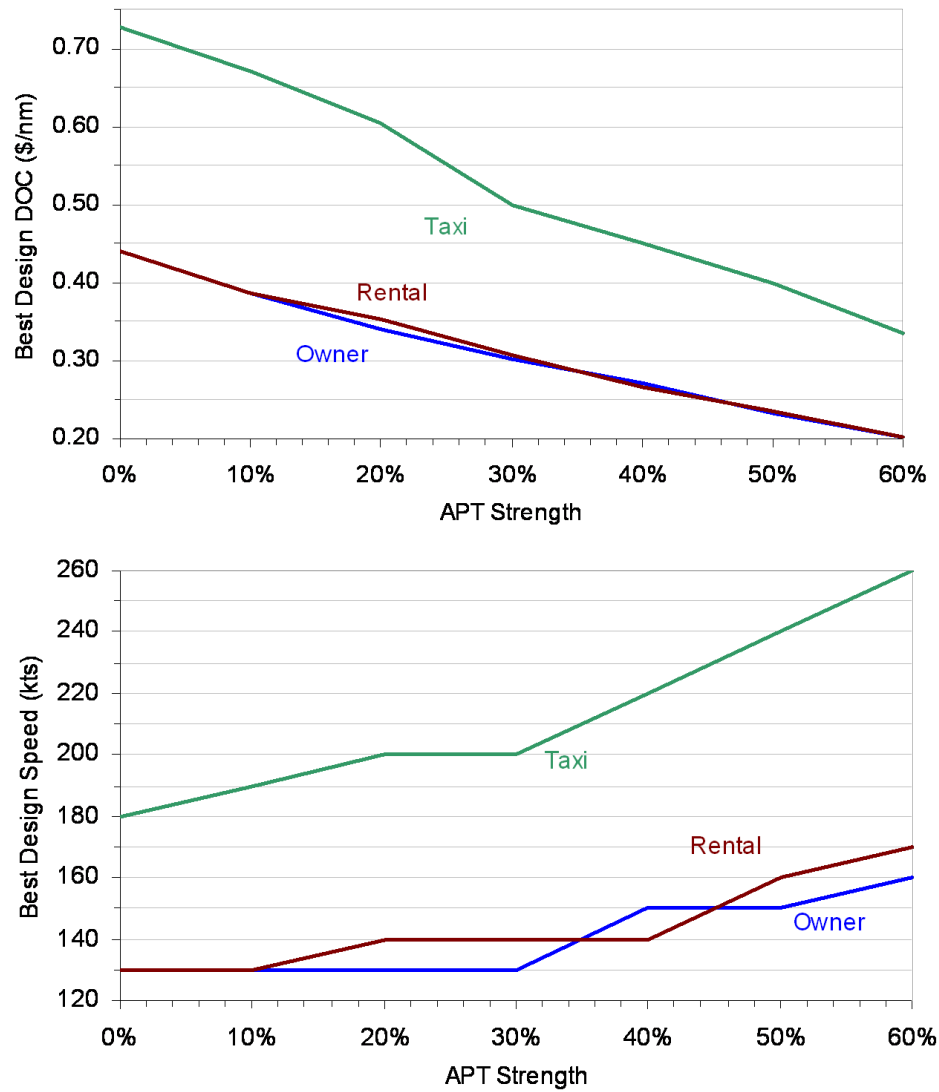


Figure 114: APT strength study results.

- Where might inter-entity cooperation improve common objectives?

This question is best addressed by the results of the multi-system design study, Section 7.3.3. The results are repeated below in Figure 115. The discussion pertaining to these results lead to the conclusion that to ensure the achievement of operation on the Pareto frontier, a cooperative effort in selecting the design speed for the manufacturer and mark up for the service provider would be required - under the hypothetical scenario that a new market had been identified. Similar findings can become apparent by closely examine the

unabridged results in Figures 103 and 104.

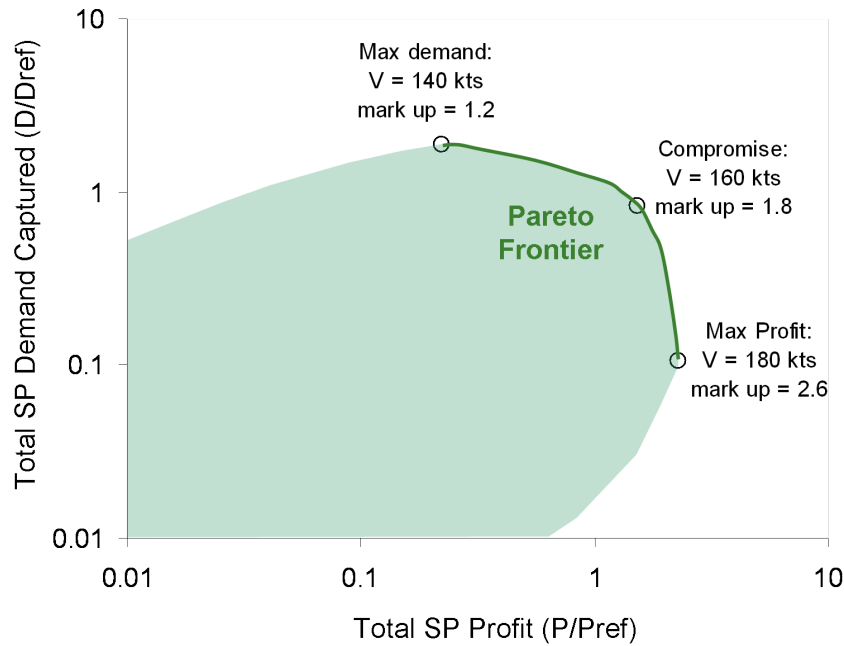


Figure 115: Simultaneous assessment of system design variables.

The demonstration of these results constitute the experimental contribution of this thesis - the demonstration that the implementation of the methodology, presented in Chapter 3, can perform as expected. Similar studies by an interested entity might help them to build a business plan - building estimations of demand volume, preferred design requirements, and the cooperation with policy planners and other entities that could make the program a greater success. This finally leads to examination of the overarching hypotheses, beginning with the methodological hypothesis, repeated below:

Methodological Research Question: How can the system of systems model best represent the interactions of the contributing systems and thus lead to a design environment?

Methodological Hypothesis: By identifying and modeling the key feasibility and viability aspects of the contributing systems, major interactions can be unveiled which can lead to “capability” based design decisions.

This hypothesis was addressed by developing a step by step methodology for systematically answering the research question, and thus provide the details asked for by the hypothesis. The presentation of this methodology constitutes the methodological contribution of this thesis, and is found in Chapter 3. Finally, the motivational research hypothesis, restated below, is addressed.

Motivational Research Question: How can conventional design methods be complemented to promote a more dynamic *and* objective design environment?

Motivational Hypothesis: A system of systems model can act as a surrogate problem definition process, and thus enable a transition from system level metrics to architecture level metrics – those metrics that represent “capability” – which can dynamically guide the design engineer.

In short, this hypothesis states that the use of system models, coupled in a common framework, will give the engineer access to architecture level metrics. These metrics would diminish the difficulty of vehicle system trades, as the measures of “success” would provide a direct indication of the products capability. Utilizing the system of systems model developed in this research, a set of results has been put together to address this hypothesis. Figure 116 shows a design space of two design requirements, overlaid with contours of the acquisition cost and direct operating cost - an exemplification of how the traditional design process might be guided.

The designer in this case might be faced with the decision of where along these constraints the design point should be. Furthermore, they may ask whether these cost constraints make sense under the hypothetical consideration of an evolving future. In Figure 117 the contours of viably captured demand have been superimposed into the situation, exemplifying the guidance provided to the engineer after implementation of the methodology.

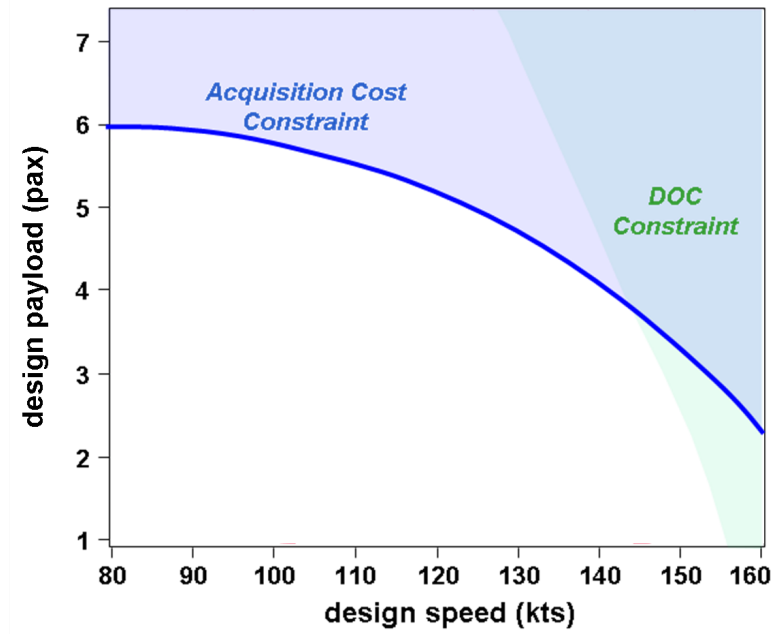


Figure 116: Example requirements trade space with traditional cost constraints.

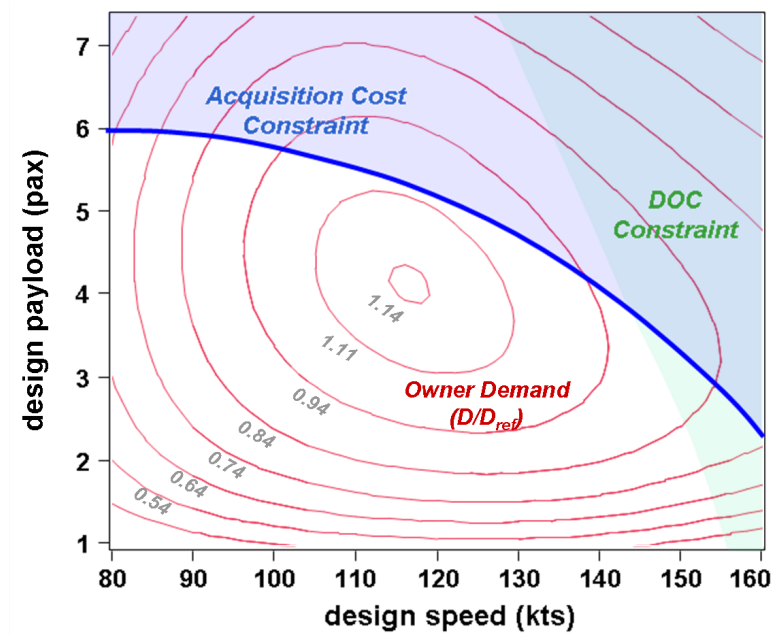


Figure 117: Example requirements trade space with demand contours.

With this capability, a design engineer can autonomously explore a design space, compare concepts, compare and study technologies, and assess the impact of driver and disruptor scenarios with a commonly comparable set of metrics. In between design and problem

specification iterations, the engineer can extrapolate information from previous surveys, and when new surveys are performed, compare results, and update the consumer representation.

In conclusion, the original purpose of developing and demonstrating this methodology was focused on the aircraft engineer, but after review of the past literature, and analysis of the model results, there is a potential for its use by aircraft engineers, policy makers, and business strategists alike. Within industry for example, this capability could help explore markets that exist or find ones that do not exist by examining hypothetical scenarios - implementation of future technologies, infrastructures, etc. It might also act as a common environment within an entity, for example to strengthen the connection between the engineer and business strategist, or between entities, for example to aide in communicating design and operational ideas between a manufacturer and service provider. As a policy planning tool it might be used to determine what technologies government institutions should promote, and what types of research to fund.

8.2 Future Work

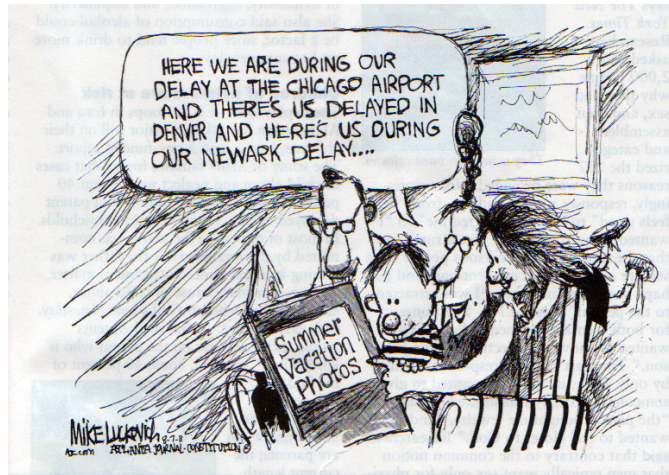
The complexity of the GA transportation system, for which this and previous research attempts to simulate, is a daunting endeavour, and in all likelihood is always subject to improvement - growing the systems which the model encompasses and implementing detail. To this end, included here are a small list of recommendations for future enhancements, and what might be gained by their implementation.

- Competition effects - As was noted in the results, competition among manufacturers and among service providers can have vast effects on the ability to capture demand, especially when pursuing a design to capture multiple markets. Competition simulation requires giving sentience to the service provider and manufacturer entities, as well as strategies for pursuing their objectives.
- Unscheduled Maintenance - In reference to the discussion in Section 6.1.3, the effects of unscheduled maintenance, and furthermore how they might affect design decisions would be a topic of specific interest to the service provider.

- Fuzzy Quantities - Consumers make travel and purchase decisions not only on the measurable quantities, including time and cost, but possibly as much or more on less measurable quantities such as comfort, safety features, aesthetics, and quality. The concepts of fuzzy logic and reasoning (see for example Zadeh (1975)) may be applicable to building a decision model - although a customer survey, or similar, will be required to “teach” the model.
- Licensing Model - An important effect to address is the impact that technology, both in the direct, on-board easy-to-fly potentials, as well as the indirect effect of reduced purchase and operational cost has on inducing consumers to become licensed pilots.
- Demand surrogate - The demand model consumes 95% of computation time in the current research. Because a large number of variables are passed among all models, and because agents are governed by probabilistic choices, accurate surrogate modeling was unsuccessful in the current work.
- Network Model - A network model can assess impacts of local traffic, noise, and emissions impact, all of which may be considered important metrics in a future GA transportation system.

Appendix A

AIR TRAVEL STATISTICS



With the exception of a few momentary slumps, such as deregulation and 9/11, the demand for air travel has steadily increased. This trend is seen in the annual enplanements by commercial airlines plotted in Figure 118. Each enplanement represents one paying passenger boarding an aircraft, which is a good indicator of the nation's air travel demand, assuming that the capacity is available. Figure 118 also includes the FAA's predictions of demands for enplanements up to 2020, at which time it is expected that the demand will increase by over half, to 1.2 billion enplanements annually, and a near doubling by 2030.

Annual Commercial Airline Enplanements (millions)

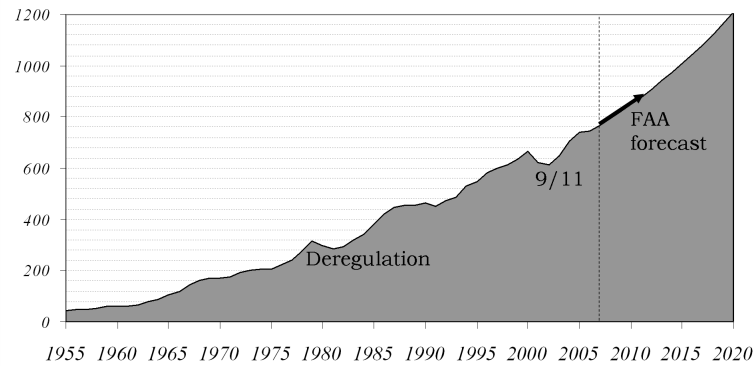


Figure 118: Annual enplanements from FAA (2007a).

The FAA model used for this prediction only considers factors for demand, and assumes the necessary capacity will be available. Another FAA study considers the control tower operations and aircraft fleet size increases that would be necessary to achieve a capacity that meets the predicted demand. The predicted levels are plotted in Figure 119, and show that the fleet size and operations will require a nearly point for point increase, i.e. both predictions indicate a 50% increase by 2020 and a doubling by 2030 (FAA, 2006).

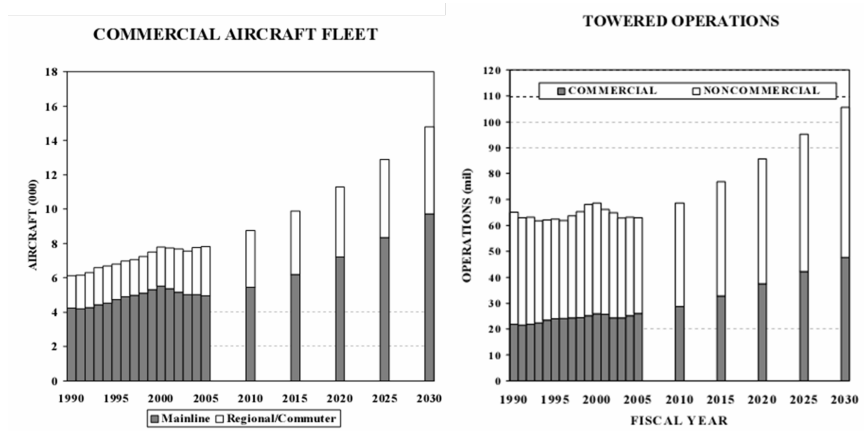


Figure 119: Historical and predicted fleet size (left) and operations (right).

To begin, accounting for such increases in fleet and operations is a long stretch for such a short period of time. For airliners, increasing the fleet size by 3,000 aircraft is impractical. This would require hundreds of billions of dollars for the purchase of aircraft

and maintenance, and a re-organization of ancient logistics systems. All this needs to occur while fare yields continue to decrease, regional carriers come in and out of existence like lightning bugs, and commercial airliners balance on the edge of bankruptcy. Commercial airliners cannot afford this burden and would be exposed to an increased amount of risk to market volatility.

For the FAA, a federal government organization, this means a restructuring of operations along with billions of dollars in building a new and improved air traffic control system ¹. Increased number of operations also calls for an increase in the number of runways at the major hubs. This brings another entity, the local government or organization of each airport. Numerous runway improvements plans are currently underway (FAA, 2003).

Taking into account the expenditures and logistics required across industry, federal, and local governments as noted above, the chances that future capacity will keep pace with rising demands is grim. Because the majority of commercial air carriers go through a small number of hubs, the problem of delays has the potential to increase at exponential rates. A study of the impact of civil aviation on the national economy suggested that even with highly aggressive runway and air traffic control improvement schedules, air travel delays could increase by nearly 40% (AIA, 2002). Air carriers may be able to relieve some pressure through increasing the number of point-to-point flights, but with an already marginal yield on operation using a more economically efficient hub-and-spoke system, this is far from a dependable solution.

The problem of lacking infrastructure is not a future problem, it is already occurring. Today, passengers are experiencing more delays, and the trend is increasing as implied earlier. On top of this, the comfort level is decreasing. To start, airline deregulation brought about increased competition, which means less attention paid to the customers. This resulted in narrower seating, longer lines, and a reduction in service quality, which continues today (Kahn, 2007). Also, the emergence of low-cost, regional carriers, which come in and steal a select number of highly efficient routes, have forced further pressure on the mainline carriers.

¹The issue is now being addressed by the U.S. Secretary of Transportation as an urgent need for a next generation satellite based air traffic control system (FAA (2007c)).

Another malady of this scenario is increasing load factors. For mainline carriers, the average load factor has increased from around 0.60 in 1990 to 0.78 in 2006, and for regional carriers from 0.47 in 1990 to 0.72 in 2006. This translates into a much less pleasurable trip for the passengers.

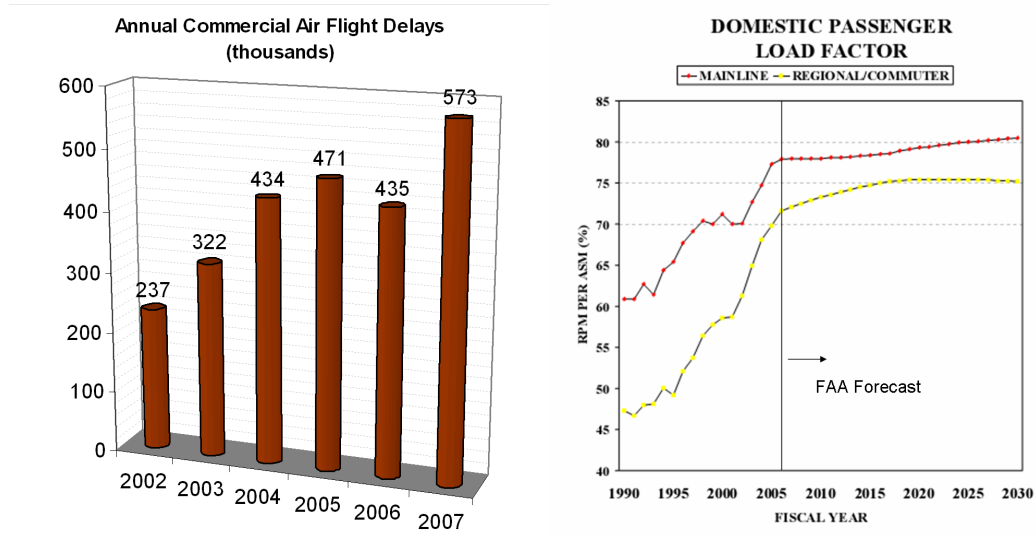


Figure 120: Annual delays (left) and load factors (right).

Recognizing the current condition, and the expectation for demand growth, there is little doubt that future passengers will increasingly experience inconvenience through delays, load factors, and poor service, not to mention lost baggage, long security lines, and parking hassles. So far, the factor that has been assuring commercial air carriers a secured market is the low fare prices induced by competition. But, if demand continues to grow, and capacity does not follow, the customers are at risk of losing the market, and may experience demand driven high fares to go along with the degraded comfort.

This may be enough to push a significant number of customers to pursue and accept alternative solutions. In fact, we have already begun to see the high-end customers pursue an alternative to the commercial airline. In the last several years, there has been a very large jump in the demand and shipment of business jets and on-demand charter service (Smith, 2006*b*). This implies that the customers who value time and comfort very highly are willing to pay more for a shorter and more comfortable flight.

Because there is such a high expectation of future demand, and a low chance of the

commercial airliners of meeting the capacity, there is a large potential market for the unmet demand. If we consider, for example that the commercial airline sector can increase capacity by 25% by 2020, then that leaves an unmet demand of over 200 million enplanements per year. If we do a bit of quick math, this translates to on the order of 70 million round trips, about 35 billion passenger flight miles, and thus a potential 180 million GA passenger flight hours ². If we make the same assumptions up to 2030, then we can expect nearly 540 million potential GA flight hours. The entire GA fleet, including non-travel use, booked a mere total of 27 million flight hours on a total fleet of 224,352 aircraft last year (GAMA, 2006*b*). Considering that most of those hours were done on less than 50% of those aircraft, there is a potential for up to 2 million GA aircraft.

²Assume about 3 enplanements and 500 miles per round-trip per passenger, and a 200 mph GA flight speed.

Appendix B

DESIGN PERSPECTIVES

This appendix brings perspectives to the modeling processes involved when deriving the methodology, presented in Chapter 3, as well as during the implementation process.

B.1 The New Paradigm in Aerospace Engineering

In traditional aerospace conceptual design, the process of requirements definition, vehicle concept generation, and vehicle concept selection was a fairly serial “round table” process, consisting of the subjective input of experienced policy makers and engineers. As requirements became more ambiguous and budgets became more constrained, the impracticality of this process began to show. It was evident that to adhere to smaller budgets, the many proof-of-concept projects, focused on achieving specific performance goals, were very expensive. This occurred in the military world due to the disintegration of Cold War threat, which provided large budgets for well defined performance goals, and in the industrial world due to the increasing global competition, requiring a further focus on the affordability of products. Thus the new paradigm in aerospace engineering, along with other industries, became “design for affordability”.

A large reason for large expenditures in the past was due to the expense of design changes late in the process. Under the recognition that the majority of the cost and quality of the design is locked down at the moment of concept selection, the conceptual design process has become highly emphasized. This idea is commonly illustrated as the knowledge-cost-freedom diagram, displayed in Figure 122 from Mavris and DeLaurentis (2000). A motivating discussion of this topic is given by Schrage (1999). Under this new paradigm, the primary goal is to shift focus on upfront analysis and comparison of potential concepts, such that we gain as much knowledge about each concept in relation to potential uncertainties and to one another. In this manner, decision makers should be able to make the choice of concept from

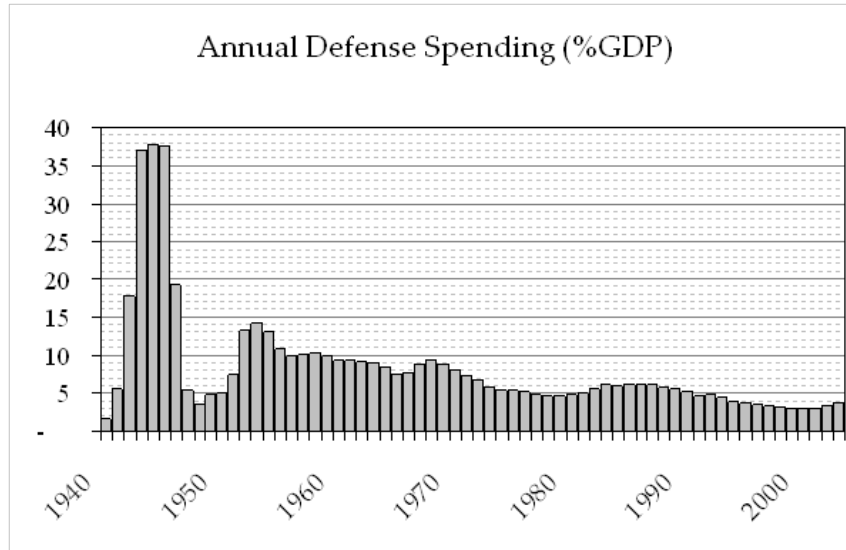


Figure 121: Annual defense spending (1940-2007) (OMB, 2004)

a very large pool of analyzed concepts that will meet a more understood set of requirements, with an acceptable possibility of failure and/or costly design changes.

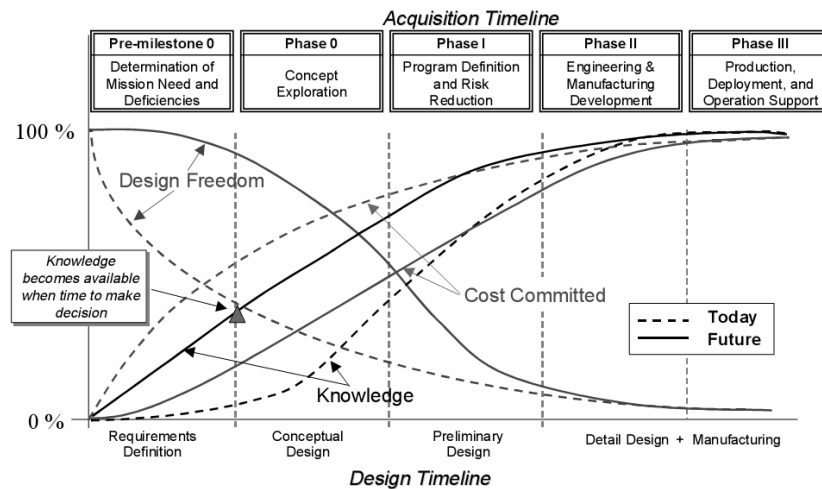


Figure 122: Knowledge-Cost-Freedom shift towards the “new paradigm”.

To enable these extensive tradeoffs between concepts, technologies, and requirements, a number of tools began to surface. These tools allow more tractable means of requirements definition and parametric understanding of requirements, technologies, and concepts, as well as tools that enable the characterization and quantification of process uncertainty, the simultaneous optimization of many vehicle concepts, and processes for the simultaneous

analysis of many vehicle objectives. In this section, a number representative methods will be presented. The methods have been generalized into categories of requirements synthesis and concept selection, although there is some overlap.

B.2 System of Systems

System of systems (SoS) is a term that arose to describe systems that are composed of individual components that are considered as, to some degree, self operating systems, and that together achieve some behavior which might not otherwise occur. Initially, the term was aimed at emergent intelligent systems, for example a distributed air defense system, where each defense station could independently sense and destroy a local threat, and each station could also relate information between all other stations for an enhanced collaborative operation. But since its inception, the term has come to describe any system that is composed of individual systems, although many have also attempted to fashion more rigorous definitions. For example the International Council on Systems Engineering (INCOSE) claims that a digital camera constitutes a SoS, where by more rigorous definitions, it would not be considered as such (INCOSE, 2006). Sage and Cuppan summarize five characteristics that a candidate SoS should have that will most appropriately call for a SoS designation (Sage and Cuppan, 2001). The characteristics are listed here with interpretations by the author:

- Operational Independence of the Individual Systems: Component systems are able to perform useful operations independent of one another.
- Managerial Independence of the Systems: Component systems are managed independent of one another.
- Geographic Distribution: Component systems are spatially dispersed, and exchange mainly information.
- Emergent Behavior: As a SoS, behavior arises that might not otherwise be achievable, and without a common orchestration.
- Evolutionary Development: A SoS is always expandable from its current state, and

due to its very large nature, must start from and progress through stable intermediate forms.

Another good descriptor would be “non-centralized”, in that the emergent behavior (which we may or may not be intended) is not the result of a centralized command, it is from the collective influence between all systems. Maier, who contributed to the above list, gives a general definition which states “1) [SoS] component systems fulfill valid purposes in their own right and continue to operate to fulfill those purposes if disassembled from the overall system, and 2) the component systems are managed (at least in part) for their own purposes rather than the purposes of the whole” (Maier, 1998). This seems to be a good general definition for most purposes, but the literature has many varying perspectives. Maier also suggests a very useful taxonomy to describe SoS, and its use could potentially help to allow the use of the term without extended philosophical discussion on whether it is being used correctly. Three classifications of SoS are given, which are repeated in part here:

Directed: Directed systems-of-systems are those in which the integrated system-of-systems is built and managed to fulfill specific purposes.

Voluntary or Collaborative: Collaborative systems-of-systems are distinct from directed systems in that the central management organization does not have coercive power to run the system.

Virtual: Virtual systems-of-systems lack both central management authority and centrally agreed upon purposes. Large-scale behavior emerges, and may be desirable, but the supersystem must rely upon relatively invisible mechanisms to maintain it.

The NTS and GA architectures clearly do not fall into the directed SoS class. The GA architecture (aircraft, service providers, and flight operations) leans more towards the collaborative class while the NTS as a whole (all travel modes and their architectures, travelers, all infrastructures) leans towards the virtual classification.

The SoS concept emerged as a perspective for system engineering design, implying that a SoS is being developed. The perspective is also useful in application to modeling a SoS that

wholly or partially exists. Such a model could be useful for the purpose of a single component system design or for the purpose of forecasting future behavior of existing large and complex systems, without necessarily implementing any design efforts¹. For example, DeLaurentis and Callaway call for rigorous decomposition of the NTS (an existing SoS) into a SoS model, to “enable our decision makers to evaluate whether decisions to authorize spending trillions of dollars on an infrastructure project, implement a particular public policy, or develop a new piece of technology are together good, bad, or indifferent for the nation over a generation or more” (DeLaurentis and Callaway, 2004). DeLaurentis then went on to define such a SoS lexicon for the modeling perspective as exemplified in Figure 123.

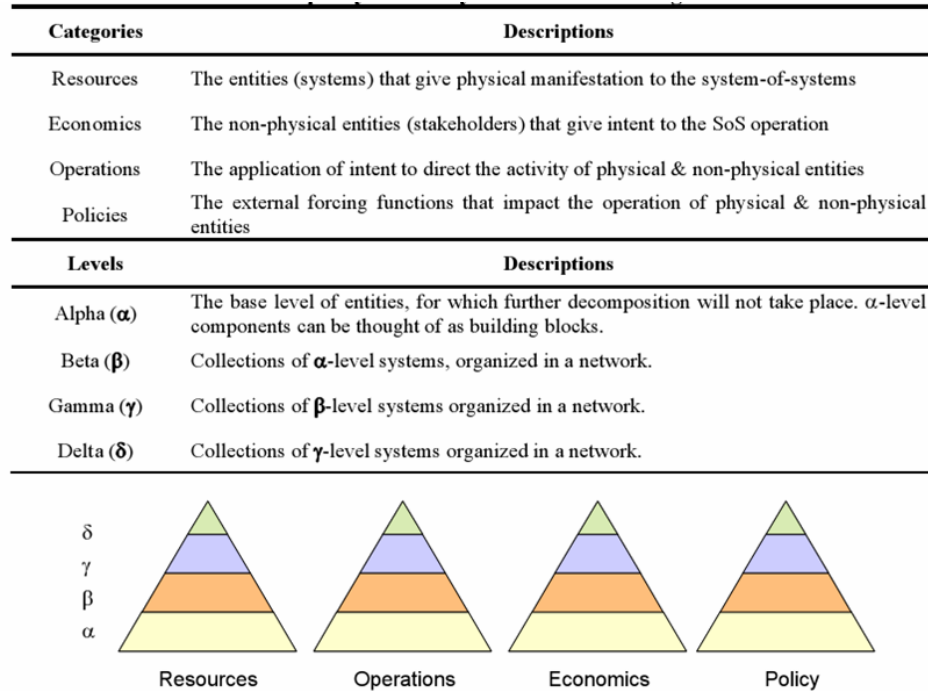


Figure 123: DeLaurentis’ SoS lexicon and “unfolded pyramid” of the NTS.

In this case, the NTS is not a new SoS. In this case the SoS terminology is utilized to characterize the modeling environment. As a modeling perspective, this perspective helps us to approach the complex problems in a less formidable manner. This is achieved by treating systems as separate entities, and then bringing them together in a common

¹The results might be used for policy planning or general preparedness, i.e. examining the probability that the SoS fails or causes catastrophe in the future.

environment. This is in contrary to building a “ground-up” monolithic model of a complex SoS. Theoretically, we will have a SoS model in which each system model can stand-alone, but can also react to changes in other systems. This brings about a distinction between SoS design and SoS modeling². SoS design implies that we are interested in designing a SoS which could be entirely new, and SoS modeling implies that we are interested in characterizing the behavior of a SoS. The SoS model could represent a completely new SoS, such as the aforementioned missile defense system, or a completely existent, and possibly uncontrollable, SoS, such as global weather modeling. In most typical cases, as with GA vehicle design, there will be a hybrid scenario, such that a SoS model will be used to design one or more component systems, and other component systems are out of our control. Utilizing a SoS perspective for modeling complex systems has the following advantages:

- Modeling flexibility: Component system models can be interchanged as they are improved or added as knowledge and understanding increases.
- Component systems can be complex: Each component system could be created, managed, and interpreted by individuals or departments that have expertise. A system engineer manages the interactions between systems, even under geographic distribution.
- Comprehendable Evolution: Component systems act as stand-alone models, so they can be individually developed and implemented into the SoS model. Thus one can start with a core framework, and build a series “stable intermediate forms” towards an increasingly detailed model.

In application to this thesis, the SoS perspective will provide an excellent means of building a SoS model, consisting of the primary components of vehicle, demand, and operations³. The primary goal of the model is to provide the estimate of “capability” to be applied to the capability-based perspective. The SoS, as opposed to monolithic, framework provides

²SoS design will typically require the use of a SoS model.

³This is the current status of the component system models. Each of these system models could be further decomposed into component system models.

a means to start at a swallowable “stable intermediate form”, with the flexibility to work towards increased detail. Further, it readily allows the manipulation of vehicle design and interchangeability of vehicle models. This model is initially aimed at use for vehicle system design, but can eventually be utilized as a means of SoS design, rather than just vehicle system design, by simultaneously designing the components of the GA architecture⁴, as well as other alternative architectures⁵.

B.3 The Capabilities-Based Approach

The capabilities-based approach can be thought of as a perspective for the design, planning, and acquisition of resources that provide a successful capability under variations, both static possibilities and dynamic changes, of future scenarios. Davis provides a good description of an analytic architecture for capabilities-based planning, with specific application to defense forces planning, but with the following general definitions (adapted from Davis (2002)):

Capabilities-based Planning: Planning, under uncertainty, to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice.

Capabilities: The general potential or wherewithal to deal effectively not just with a well-defined single problem, but with a host of potential challenges and circumstances.

In the defense world, this approach is being pursued in part to find ways to plan for an armed forces, as a whole, that has the capability to robustly deal with a number of possible threat scenarios⁶ while working within a budget. This potentially solves the expensive process of force planning based on a “worst-worst-case-scenario”, which is known as the bounding-threat method. Also, the expenses associated with force redundancy, due to individual force planning by each branch of the armed forces (Aldridge, 2004). The defense strategy

⁴The GA architecture, composed of several systems, could be thought of as a deployable SoS, with an effort to simultaneously design vehicle systems, service provider operations, navigational and air traffic control infrastructures, and any other systems.

⁵The simultaneous design can be thought of as a collaborative effort among the component systems to achieve capability, or as a more virtual scenario, where various architectures are competitive in nature.

⁶Although threat scenarios can be modeled around real-world enemies, the list of scenarios encompasses any possible future threat types, e.g. rogue nation, dispersed terrorism, etc.

for capability-based planning is probably the most recent and large scale application⁷, but similar efforts have been in place for some time in various areas.

In industry, capabilities-based planning provides a competitive advantage in robustly planning for a dynamic future, rather than optimizing for “business as usual”. For example, Levi Strauss guided their resource planning to be adaptable to scenarios of cotton deregulation and large-scale “cotton epidemics”, while still performing effectively in the most likely scenarios (Epstein, 1998). The approach has been applied to policy planning as well, since planning to a single future prediction can often result in policies that fail when an alternate future presents itself. For example, Lempert and Schlesinger (2000) suggest the use of capabilities-based planning as a robust means of making policy for abating climatic change, by finding policy that would be robust to a number of unknowns in the future global condition.

So far, capabilities-based design is primarily a guiding concept. Actual methodologies to implement it are not rigorously defined in the literature, and really none is needed, because the implementation will always be problem specific. In the author’s opinion, the concept of the capabilities-based approach can be summarized as below:

- Resources and processes are designed and organized towards achieving an overarching capability. Achieving that capability necessitates satisfying end-users and stakeholders alike.
- Focus can be designing a set of fixed resources and processes that are robust to various scenarios, designing resources and processes that can robustly reorganize to meet dynamic changes, or both.
- In general the resources will satisfy that capability under a specified set or a continuum of future scenarios, that can be thought of as alternative futures (i.e. each alternate future is possible, but only one will happen), or dynamic futures (i.e. the future can dynamically evolve).

⁷Although not yet fully implemented by any means.

- The approach requires a system-of-systems perspectives, because the resources and processes (systems themselves) must interact amongst all other resources and processes, as well as with intermediate systems to achieve an over-arching capability.

Webb provides a concise set of analytical principals to consider when initiating a capabilities-based approach. (from Webb (2006), abridged):

1. Focus on outcomes (desired operational effects) of the enterprise end-user.
2. Frame a portfolio perspective as a means of partitioning the problem and solution spaces in terms of capabilities.
3. Approach issues holistically; consider a full range of alternative solutions to provide a capability.
4. Examine the complex networks of inter dependencies, at different levels of hierarchical description
5. Explicitly bound profound uncertainties attendant to complex adaptive system problems.
6. Pursue an adaptive evolutionary approach to planning to position the enterprise to effectively respond to changes as they occur.
7. Assess and balance the evolution of capabilities within the resource constraints for a wide range of diverse and stressing operational circumstances.

The Department of Defense plan for a capabilities-based approach could be considered the most generalized example. They intend to consider the simultaneous interaction of all resource systems to robustly achieve capability within a number of dynamic future scenarios. Thus they need to consider simultaneously the design of resources, the ability to reconfigure systems of these resources, the resources which will coordinate the reconfiguring, understanding the capability of systems of resources to handle various circumstances, etc. This is a very formidable task, especially if it is to be done within an integrated analysis environment.

One perspective that is not clearly defined in the literature is exactly how the capabilities-based approach should be implemented. Most of the literature suggests that the process is iterative and loosely coupled (i.e. manually pass information between decision-makers and engineers involved with the examination of scenarios, the analysis of capabilities, and the design of resources and processes), which in some cases, such as the defense scenario, may seem necessary due to the wide-spanning nature of the problem. This thesis focuses on performing capability analysis and design within a fully integrated analysis environment.

Because it is the desire to show the performance of an integrated capability-based environment, the approach in this thesis will take the following approach: create a core environment that ensures flexibility and leaves room for analysis modifications and additions. One reason this approach is taken, is that typical capabilities-based approaches focus on organization of existing resources and process, not necessarily focusing on the design of resources. The scope of this research is within the vehicle conceptual design. Hence the capability-based perspective translates into building an analysis environment that estimates the effects of vehicle design on the capability GA to support the nation's mobility. The manipulation of this environment allows the exploration, optimization, and selection of vehicles that have robust capability among a variety of future scenarios. Both the horizontal (other transportation modes) and vertical systems (travelers and operations) will be a part of the analysis environment, but will initially be of less focus in the design process. Building the environment within a modular framework will allow for future modification towards a full capability-based approach, as encompassed by Webb's principles.

B.3.1 Viably Captured Demand

It is of foremost importance to define what is meant by capability. The primary goal of an GA architecture would be to support the nation's mobility. Thus, it is considered that a proper metric for capability, with respect to design process, is viably captured demand⁸, defined as follows:

⁸It is noted that the mobility provided by the GA architecture alone may not be the final metric to assess enhancement to the nation's mobility, due to possibly negative effects of a new architecture on existing architectures. Further, there are other important factors, such as adherence to policy and service provider profits, but these will be discussed later.

Viably captured demand: The travel demand attracted by a GA architecture, which can be considered both feasible and viable.

Demand attraction implies that we must evaluate the ability of a vehicle design to have a sufficient number of travelers choose this alternative, at the price offered by the service provider. The economic constraint implies a viability criteria of the service provider. It also implies that the service provider can logistically service some portion of the demand utilizing its fleet of vehicles, and can do so in a profitable manner at the price that attracted the demand.

To gain understanding of the processes of estimating the viably captured demand, including matching demand attraction and operational viability, a notional progression will be provided. This progression will exemplify the flow of information necessary to translate the vehicle specific costs and performance to the estimation of viably captured demand. Following this progression, a top-level flow of information will be displayed as a general modeling blueprint. Finally, the application of the capability-based perspective to the GA design problem will be described.

We start with Figure 124. This is a “big picture” example of how a single design variable, in this case the engine power, P_E , could impact the GA and NTS architectures. We could imagine that a decrease in engine power might increase the takeoff run, a factor that would reduce the availability of the aircraft, and thus demand for it. At the same time, reducing P_E has the effect of reducing operating cost through fuel burn, and reducing the acquisition cost through a smaller engine. These costs affect the operational costs of the service provider, and thus the ability to capture demand.

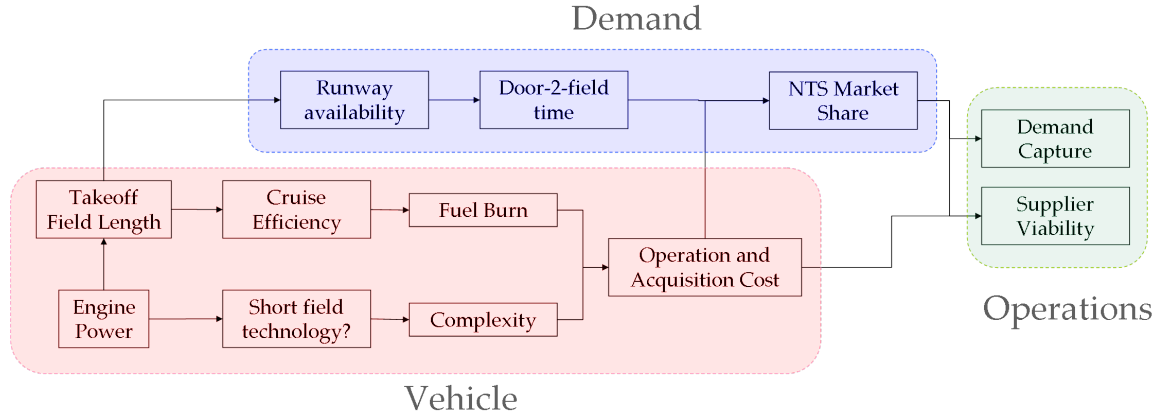


Figure 124: Example: notional design impact to GA architecture.

These processes also have varying time length. For example, the vehicle design will be fixed once it is manufactured and distributed, hence there would be some iteration, upon the release of each vehicle, between the demand side and the operations side, namely the service provider would have to adjust their operation in an attempt to optimize their profits, and with respect to possible competitors. But for now, a more static view is taken such that we get a working, understandable picture. Any process implemented should be flexible towards such future modifications.

This was a simple example to show how one design variable can propagate through the design domain and to the capability of viably captured demand. Clearly there a number of design variables, as well as assumptions within the demand and operations domain that have strong effects on the capability. In the following notional progression, these will be treated in bulk, but the discussion should be general enough to account for all.

Demand Attraction

First, consider two design concepts, A and B (e.g. a light helicopter and a piston airplane), and two objectives, cost and performance (e.g. direct operating cost and door-to-door time), both of which are to be minimized. This simplification is for the purpose of exemplifying the process, but any processes implemented need to account for a generalization to both a large number of design concepts, and a large number of vehicle objectives. Imagine that the results of vehicle analysis were like those depicted in Figure 125. Basically, vehicle

A is of low cost but poor performance, and vehicle B is of excellent performance, but with a higher cost.

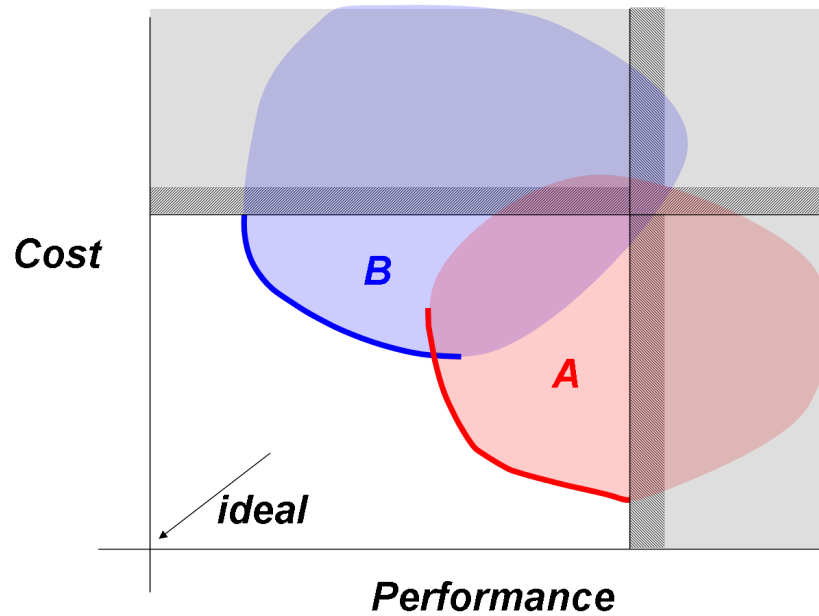


Figure 125: Notional vehicle concept optimization and selection scenario.

In Figure 125, the two concepts⁹, are represented by the shaded circles, and each concept's Pareto optimal alternatives lie along the darkened edges. Now, we are faced with making the decisions: which concept is “better”, and which particular alternative do we choose along the “better” concept's Pareto frontier. We have a few choices of how to do this: manually pick based on some subjective reasoning or possibly utilize a qualitative decision method to generate preference to objectives. But do we really have the information to make the tradeoff decision at this point? Maybe in a simple case we can use our best judgment, or pursue two concepts a little further. But, now consider that the concepts can span across millions of combinations of subsystems, a continuum of tens of continuous variables, and decisions need to be made across 5-10 objectives. We would have to rely on our subjectively generated preference to pick the best concept and alternative among all those choices.

In many cases, concept optimization and selection via subjective preferences is a necessary procedure, because at the point of decision we have gathered all the quantitative

⁹Where the term concept includes all relevant combinations of the design variables.

information we can, and then sat down and, using our best judgment, or a method such as QFD to generate “weightings”, make the final selections. But, as has been shown in the literature survey, in the GA case we have the modeling capability to help us estimate the demand generated based on the vehicle’s performance. So let’s begin by expanding into the demand domain. In Figure 126, we see notional p-D curves for two alternatives, representative of concepts A and B. To recall, the p-D curves represent the demand that a vehicle would attract (over a long period of time, e.g. in hours per year), given that it is available at a hypothetical price, p (e.g. in dollars per hour). For a fixed design, this a primary output of the demand prediction codes.

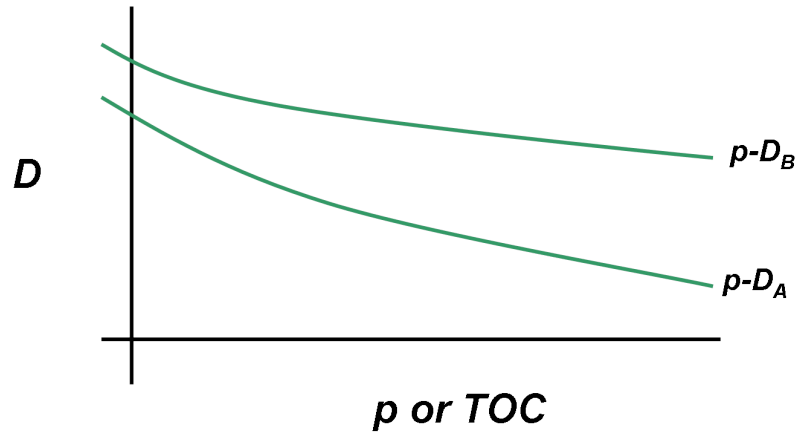


Figure 126: p-D curves of notional concepts A and B.

In Figure 126, it is apparent that vehicle B, as indicated by its p-D curve, is more attractive than vehicle A, at any given price. Recall that this p-D curve is entirely a function of the performance characteristics of the vehicle within its architecture, because the only indication of cost is the price, p , which is an independent variable. We might stop here and say “ah, vehicle B is better”. But, even though vehicle B has, for a given price, a higher demand, we do not yet know what price would give a service provider a viable operation, if in fact one existed at all. Let’s assume for a moment that this price that allows viable operation to be slightly higher than the vehicle’s TOC . Then we might find some results as depicted in Figure 127.

In this Figure, we can see a notional point of operation for each vehicle. For example, the service provider is offering the usage of vehicle A at price p_A , which is slightly above

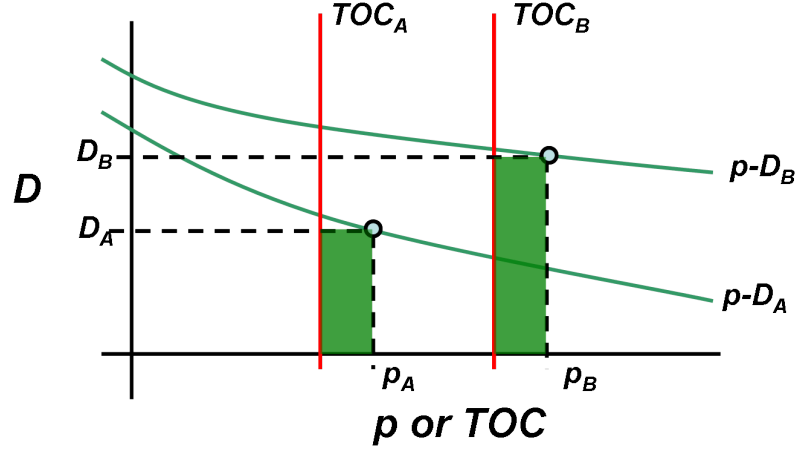


Figure 127: Operating points of notional concepts A and B.

the vehicle's TOC , and bringing in demand D_A . If one ignores all other factors, than the support of mobility would be the total demand serviced by each vehicle, that is D_A and D_B by vehicles A and B respectively. Further, the profit of each service provider would be the difference in price and cost, times the total utilization, $(p - TOC) * D$ which is the demand found at the operating point, as indicated by the shaded rectangles. In this case, it is clear that vehicle B provides a greater capability. But, this take on operating cost is too simple.

Viabale Capture

The vehicle specific costs are not the only factors coming into play when we consider the price which can be viably offered. If we consider the general case of a rental-based system, the per hour total operating cost of the vehicle includes the per hour direct operating costs, the acquisition cost of the vehicle, all maintenance and insurances, and on top of that the costs of operating the service provider business. In general, over a fixed period of time, such as one year, this amounts to yearly fixed costs, yearly per vehicle costs, and costs per hour of vehicle utilization. For exemplary purposes, we want to compare this to the p-D curve. First define the TOC to include all service provider expenditures such that the per hour total operating cost of a single vehicle could be represented as $TOC \sim DOC + b/U$. DOC is the per hour direct operating cost, b is the annual fixed costs, and U is the utilization of the vehicles, in the same units as demand D . Thus, the more the vehicles are utilized, the less the

per hour cost¹⁰. Now both p and TOC are in units of \$/hr and notionally represent the total returns and expenditures of the service provider. Also, D and U are both in units of hours, and notionally represent the total annual attracted demand and utilization respectively. If we imagine the TOC - U trend overlaid on the previous p - D diagram, we might have a result as in Figure 128.

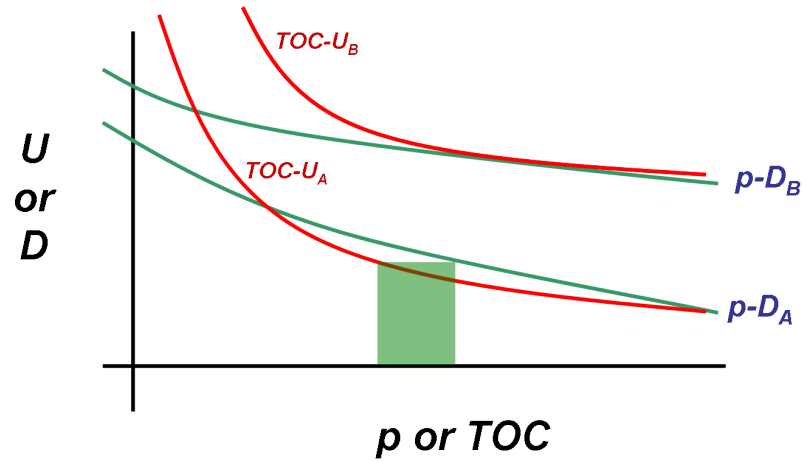


Figure 128: Notional overlay of p - D and TOC - U curves.

Figure 128 shows that we must find the a offering price which has the optimal balance of operational expenditures and returns; low to attract enough demand to reduce the per hour total operating costs, but high enough to cover the costs. This can be a very sensitive balance, and as depicted for vehicle B in Figure 128, there may not be a viable operation at all. In Figure 129, this notional example is taken a bit further by considering the effects of local demand distribution. If there are two locations, each with a local service provider, it is possible that both the local p - D curves, and the TOC - U curves are different. For example, imagine that the solid line represents a large population and the dashed line represents a population of half the size, but with similar demographics. Then, as depicted, the demand for the smaller town will be about half that of the larger town, for any given price, and the total operating costs may be slightly reduced due to the lesser costs of labor and land.

¹⁰This description of total operating cost is of course overly simplified, as we would have multiple vehicles, some amount of rejected demand, and many costs to book-keep.

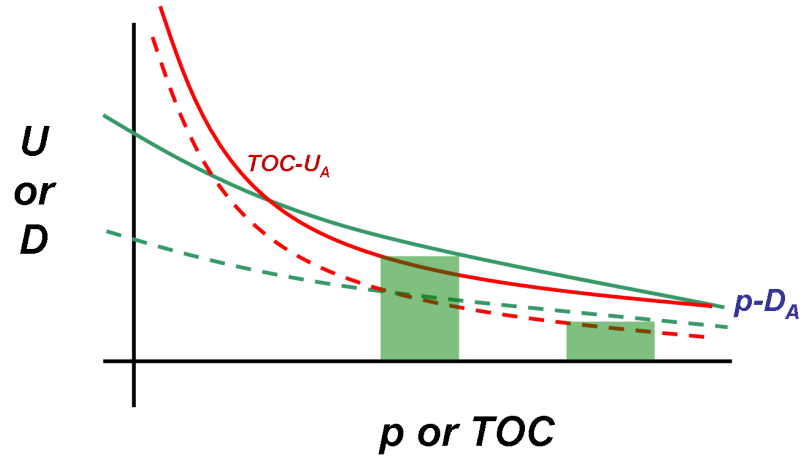


Figure 129: Notional effect of locality on demand and operations.

This progression has not covered every detail of demand and operation, but should serve as a means to display the direct mechanisms between a design's cost and performance to its architectural capability. One might consider other mechanisms that would come into play, such as the logistics of operation, policy implementation, or weather. Some of these will be considered within the time-frame of this thesis and some will not. The general idea though is that these mechanisms are details in the analysis process that should be added in a progressive manner, such that we increase the belief in our estimation. For now, the mechanisms depicted here are of direct consequence to the estimation of our capability metric, and thus will guide the core framework.

Appendix C

ADDITIONAL RESULTS

C.1 Reference Aircraft Definition

For each of the GAP and GAJ categories, a reference aircraft is created through an amalgamation of popular aircraft. A popularity weighted average of the design performance attributes of selected aircraft is calculated. The averaged attribute values become the design requirement input values for the reference aircraft in the integrated model, which is then calibrated.

The typical GAP aircraft is unarguably a four seat aircraft, as demonstrated by Turnbull (1999), where the existing GA fleet is summarized by model. This is also supported by the demand for new aircraft, as demonstrated by the share of GA piston aircraft shipments, as plotted in Figure 130, where the aircraft are ordered by their market share (1996-2006), in descending order from left to right. The top six ranking aircraft in this period are four seaters and comprise more than half of all shipments.

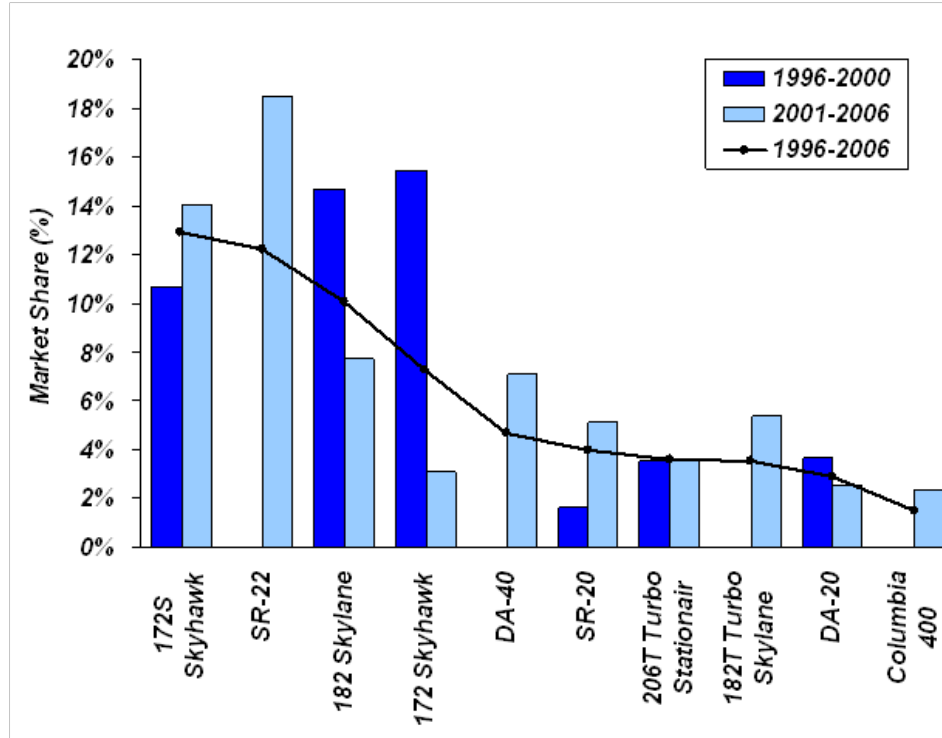


Figure 130: GA piston aircraft market share by model.

The most popular aircraft, as determined by the market share of new shipments, will be used to determine the reference aircraft. Although the most popular aircraft of the existing fleet would work equally well, the new aircraft better represent the future of GA. The primary design performance attributes of these aircraft are collected in Table 36, where the final row indicates the market share weighted average values, which become the defining values for the GAP reference aircraft. Note that the majority of the aircraft are well represented by the reference aircraft, excluding the Cessna 172 family and the Cirrus SR-22, for which the reference aircraft falls nearly in between.

Table 36: SEP design performance by market share.

Model	pax	speed (kts)	range (nm)	market share (1996-2006)
Cessna 172S	4	124	518	13%
Cirrus SR-22	4	185	811	12%
Cessna 182	4	145	773	10%
Cessna 172	4	121	580	7%
Diamond DA-40	4	145	720	5%
Cirrus SR-20	4	150	627	4%
GAP Reference	4	145	750	

The performance and cost estimates of the reference aircraft are verified against actual values of the Cessna 182, which has very similar design performance, in Table 37.

Table 37: Calculated GAP reference aircraft and actual Cessna 182 metrics.

	GAP reference	Cessna 182
TOGW	3342 lbs	3100 lbs
SHP	260 HP	230 HP
ACQ	\$322k	\$349k
DOC	\$76/hr	\$76/hr

A similar method is used to set the GAJ reference aircraft. From 1996 to 2006, Cessna has been the leading supplier of business jets, in the form of the Citation family. Also, Cessna's product specification practices make the job of accurately and consistently gathering data very simple. Thus, a market share weighted average of in-production Citation jets' design performance is calculated to create the GAJ reference aircraft. The design performance of all aircraft are found in Table 38, along with the number of aircraft shipped in 2007. The one year shipment is used in this case as the Mustang was not available in prior years.

Table 38: Cessna Citation family design cruise performance, and GAJ reference aircraft.

Model	pax	Mach	range (nm)	shipments (2007)
Mustang	4	0.59	950	45
CJ1+	5	0.68	1050	34
CJ2+	6	0.73	1100	44
CJ3	7	0.72	1350	78
XLS+	8	0.76	1550	82
GAJ Reference	7	0.71	1270	

The reference GAJ aircraft most closely represents the Citation CJ3, which is used to verify the performance and cost estimates. The verification results, displayed in Table 39, indicate that the calibrated FLOPS model is under-predicting the mission takeoff gross weight, partially accounted for by the lower design range, which propagates to the costs as well. Since the GAJ design requirement space will be evaluated, not just the reference aircraft, this error is negligible, as the model was previously verified to have acceptable results across the desired requirement ranges.

Table 39: Calculated GAJ reference aircraft and actual Cessna CJ3 metrics.

	GAJ reference	CJ3
TOGW	12,013 lbs	13,870 lbs
TOFL	3,519 ft	3,180 ft
ACQ	\$5.0M	\$6.0M
DOC	\$576/hr	\$733/hr

C.2 Reference Usage Data

Aircraft usage indicates the how and why of utilization. Four attributes have been identified to categorize the usage of GA and air taxi aircraft, listed in Table 40. Each attribute has two alternatives, resulting in 16 possible categories.

Table 40: GA usage attributes.

Attribute	Alternatives	
Aircraft	GAP	GAJ
User	Renter	Owner
Pilot	Self	Hire
Purpose	Personal	Business

The General Aviation and Air Taxi Activity Survey (GAATA) is the primary database for calibrating usage (FAA, n.d.). The GAATA survey divides usage, by flight hours, into 15 categories, four of which correspond to travel demand, and can distinguish pilot and purpose. The type of aircraft used is also recorded, and a separate part of the GAATA survey estimates usage by user.

Table 41: GAATA usage data (1000's of hours) (FAA, n.d.).

Aircraft Type	Total Hours	Per-sonal	Busi-ness	Cor-porate	Air Taxi ^z
Piston Total	16,434	7,538	2,460	394	934
One-Engine	13,739	6,794	1,842	143	381
Two-Engine	2,677	742	618	250	547
Other Piston	18	1	0	0	6
Turboprop Total	2,106	198	298	597	529
One-Engine	846	76	104	67	281
Two-Engine	1,252	122	194	530	249
Other Turboprop	8	0	0	0	0
Turbojet Total	3,771	239	306	1,884	922
Two-Engine	3,488	222	299	1,673	890
Other Turbojet	282	17	7	212	31

GAP aircraft logged 3,027,000 rental hours and 8,298,817 hours by owner (27% rental, 63% by owner). GAJ aircraft logged 971,176 rental hours and 6,158,824 hours by owner (13% rental, 87% by owner). The number of rental hours was less than the combined hours of the instructional and air taxi categories, both of which are assumed to be entirely rental

hours¹. Thus aside from air taxi hours, which are hired rental by definition, an assumption was made that 2% of GAP and GAJ personal hours and 5% of GAP business hours as self-piloted rental.

Corporate hours are defined by a business that owns the aircraft and utilizes a hired flight crew. Business and personal hours are assumed to be self-piloted, and the purpose is self explanatory. Air taxi hours, by definition, are by rental and with a hired crew. The purpose for these hours are not specified, and thus they were split evenly between personal and business use.

GAATA flight hours are converted into values of trip demand, by assuming an average speed and round-trip travel distance for each aircraft type category. The average round trip speed and distance assumptions for hour to trip conversion are 160 mph and 800 miles for GAP, and 300 mph and 1200 miles for GAJ. After conversion the importance of GAJ aircraft becomes emphasized. While the number of hours logged is considerably less than that of GAP aircraft, they travel twice as fast and thus can perform more trips with less time. GAP aircraft logged a total of 11,326,000 hours which translated to 1,832,000 trips, while GAJ aircraft logged 7,137,000 hours which translated into 1,784,250. In terms of trips, GAP and GAJ split the GA and air taxi travel demand markets fairly evenly. The combined total of GAP and GAJ aircraft logged approximately 3.6 million trips, slightly less than estimated by the ATS

Finally, the usage is classified into the 16 categories, as described by the four two-level usage attributes. The resulting percentage of the total 3.6 million trips of each category is displayed in Figure 131. Each horizontal level in Figure 131 adds up to 100%, and the bottom most level indicates the 16 fully described categories. Several characterizations become clear from this graphic. First, GAP and GAJ split the market fairly evenly. GAP aircraft are used three to one for personal travel, while GAJ are used two to one for business travel. Under GAP, the dominant usage is by self-piloted owners for personal travel, with some additional use for business travel. For GAJ, the corporate jet, described as owned and

¹Some students use a personally owned aircraft for instruction, but no records exist as to the magnitude of usage hours.

crewed for business use, is the most used. A surprisingly large percentage of GAJ use is also by self-piloted owners, most likely coming from the twin piston and turboprop categories. What is commonly referred to as air taxi, or chartered, is represented by all categories with attributes rent and hire. In total, air taxi contributes approximately 17% of all trips, with GAJ aircraft performing the majority of these operations.

C.3 Calibration to Reference Datum

Calibration is performed with runs of one million agents, representing slightly less than 1% of the total US households. The fleet distribution is first calibrated, followed by usage calibration. After integration of all models, additional calibration is required that accounts for demand lost when a service provider is not available.

The GAP and GAJ fleet distributions as described above are calibrated through adjustment of the respective ownership decision models. The aviation enthusiast fraction was considered the primary calibration variable for GAP aircraft, and the reference aircraft price utilized in the corporate ownership model as the primary GAJ calibration factor. These fleets are calibrated to within 5% of the GAMA value.

The GA use attribute distribution, as described above is then used. Calibration is performed with the adjustment of travel budgets for those using owned vehicles, and a nuisance factor for other agents.

Agents having aircraft ownership only consider direct operating costs during mode selection, as the acquisition cost and indirect operating costs are considered within the ownership choice model. The ownership choice model is implemented after the agent completes their entire travel agenda², and the acquisition and indirect operating costs are converted to an equivalent annual cost. If the agent chooses ownership based on the utility, M_i proceeds to the next agent, otherwise, the agent's travel agenda is re-simulated and recorded without ownership.

The use of GA is also assumed to be influenced by non-measurable biases. Thus, calibration factors are added to the mode choice model which are dependent upon mode and

²An agent is first presumed ownership if they meet the criteria given in section 5.2.2.

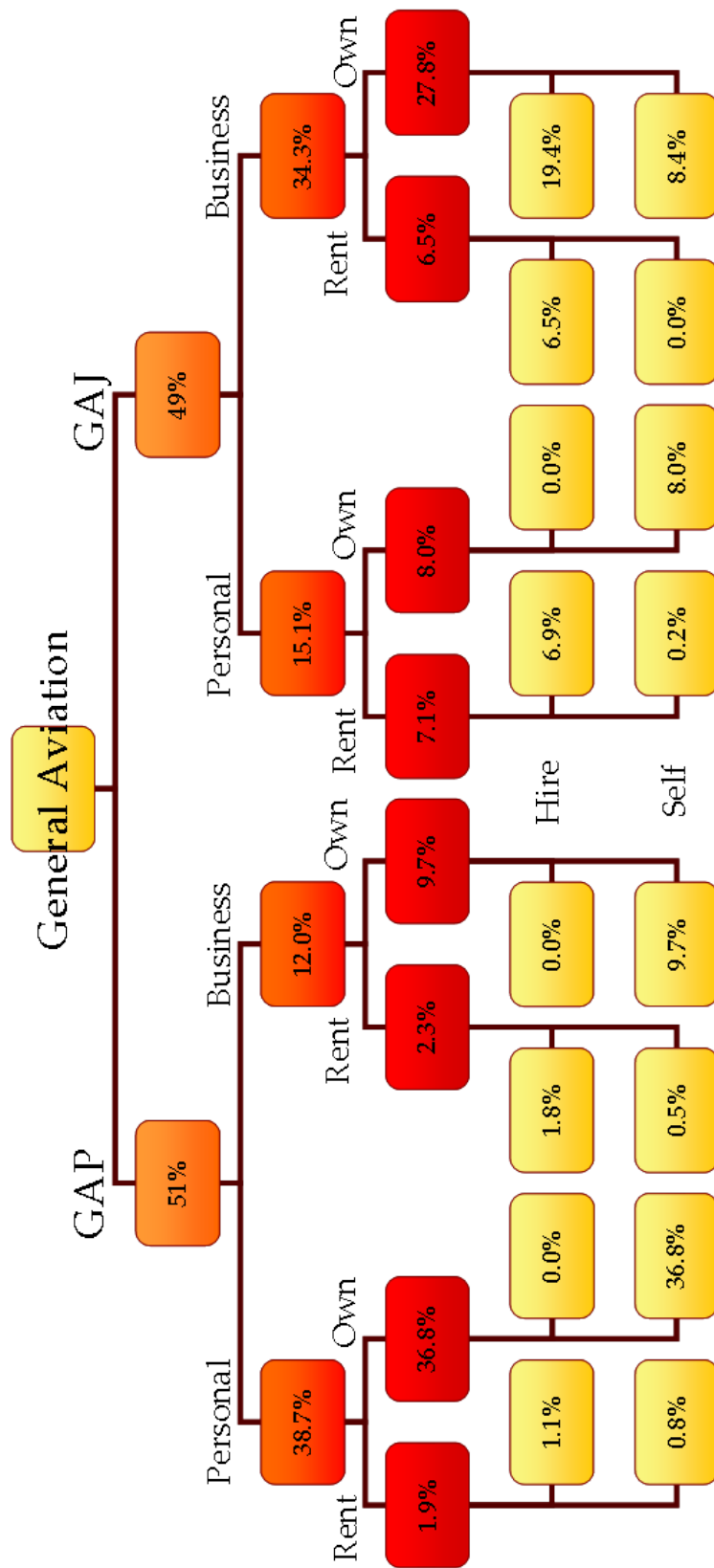


Figure 131: GA and air taxi usage distribution.

licensing attributes. While favor is applied to the utility for the purposes of mode choice, it is not applied when calculating the utility of ownership for potential owners.

A qualitative summary of the calibration process is as follows:

- GAJ owners require an increase in travel budgets, an expected necessity for owning a GAJ.
- Non-corporate GAJ owners were unable to reach the expected level, likely an artifact of combining turbojet, turboprop, and multi-engine piston aircraft into the GAJ definition.
- GAP owners require favor towards utilizing their aircraft, implying the aviation enthusiast.
- GAP renters require favor, again implying the aviation enthusiast.
- GAP and GAJ air taxi users required a moderate disfavoring, implying a lack of familiarity and comfort in using the modes.

The final calibration results for each of the 16 categories are plotted, by annual trips in Figure 132, where the model results have been scaled to correspond to a full population of 116 million households.

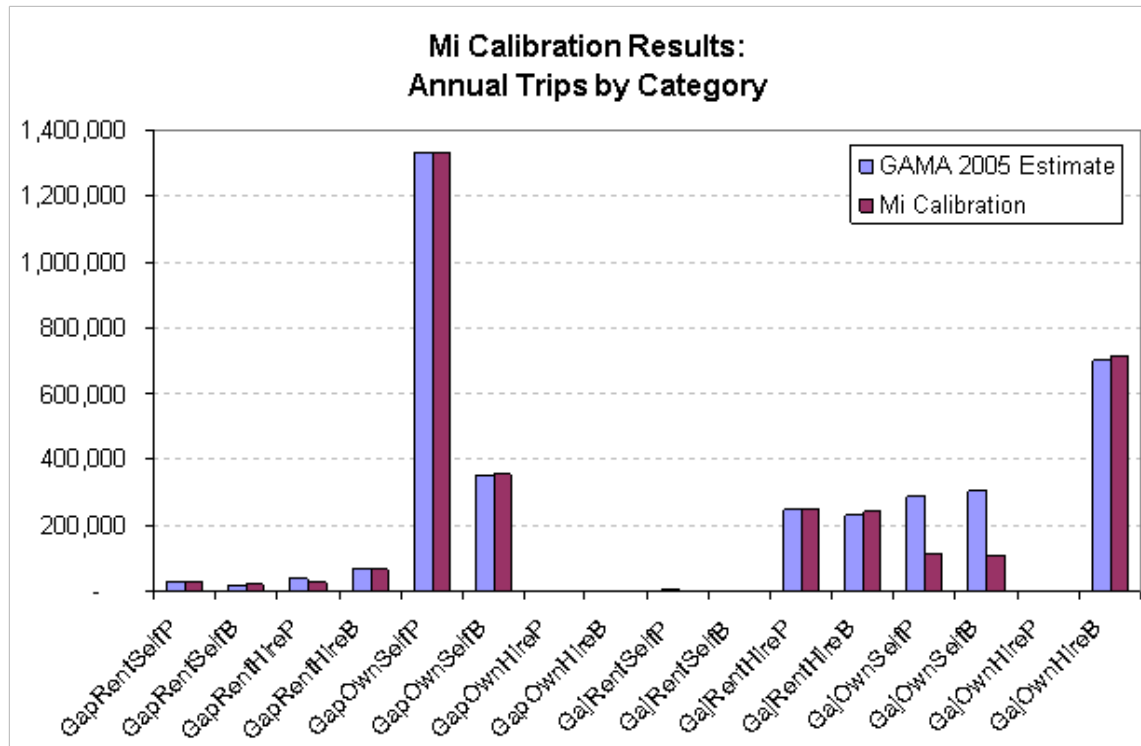


Figure 132: Usage calibration results.

C.4 GAP: Technology Implementation

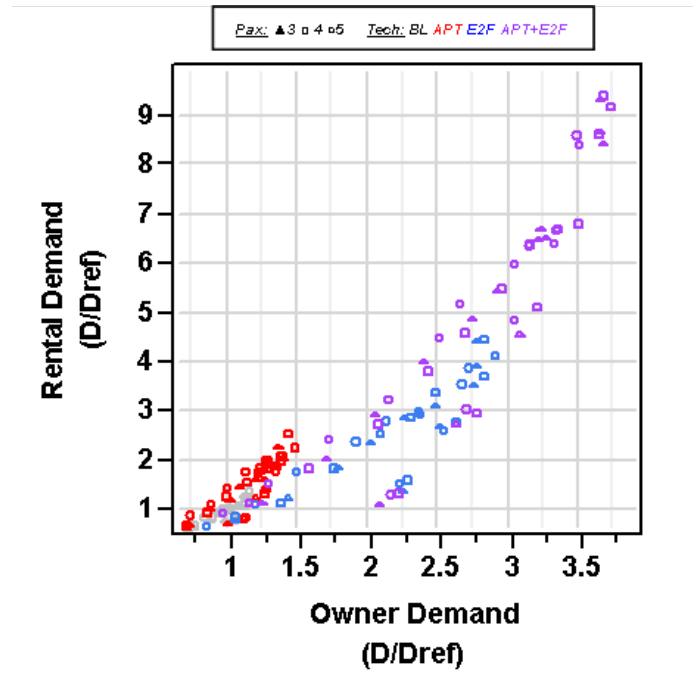


Figure 133: Demand space: rental vs. owner.

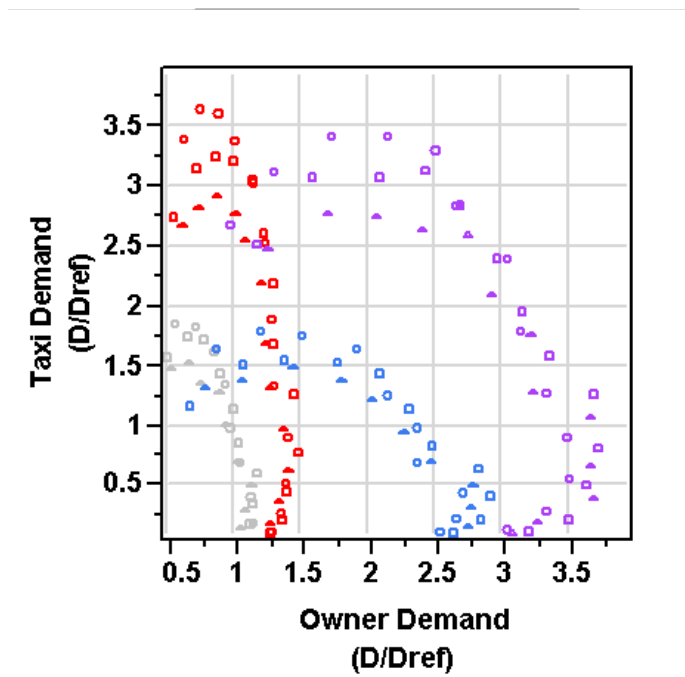


Figure 134: Demand space: taxi vs. owner.

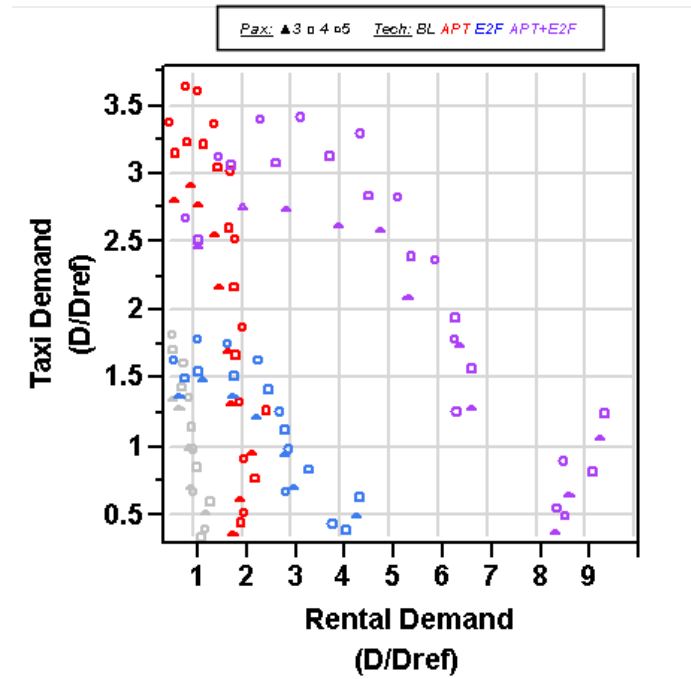


Figure 135: Demand space: taxi vs. rental.

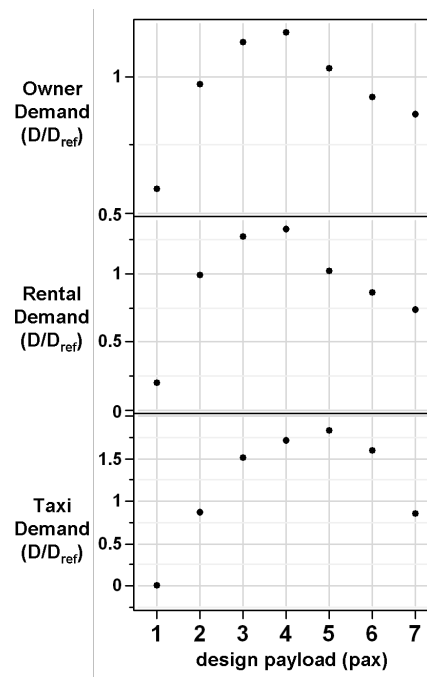


Figure 136: Captured demand (y-axis) against design payload (x-axis); $V = 145$ kts.

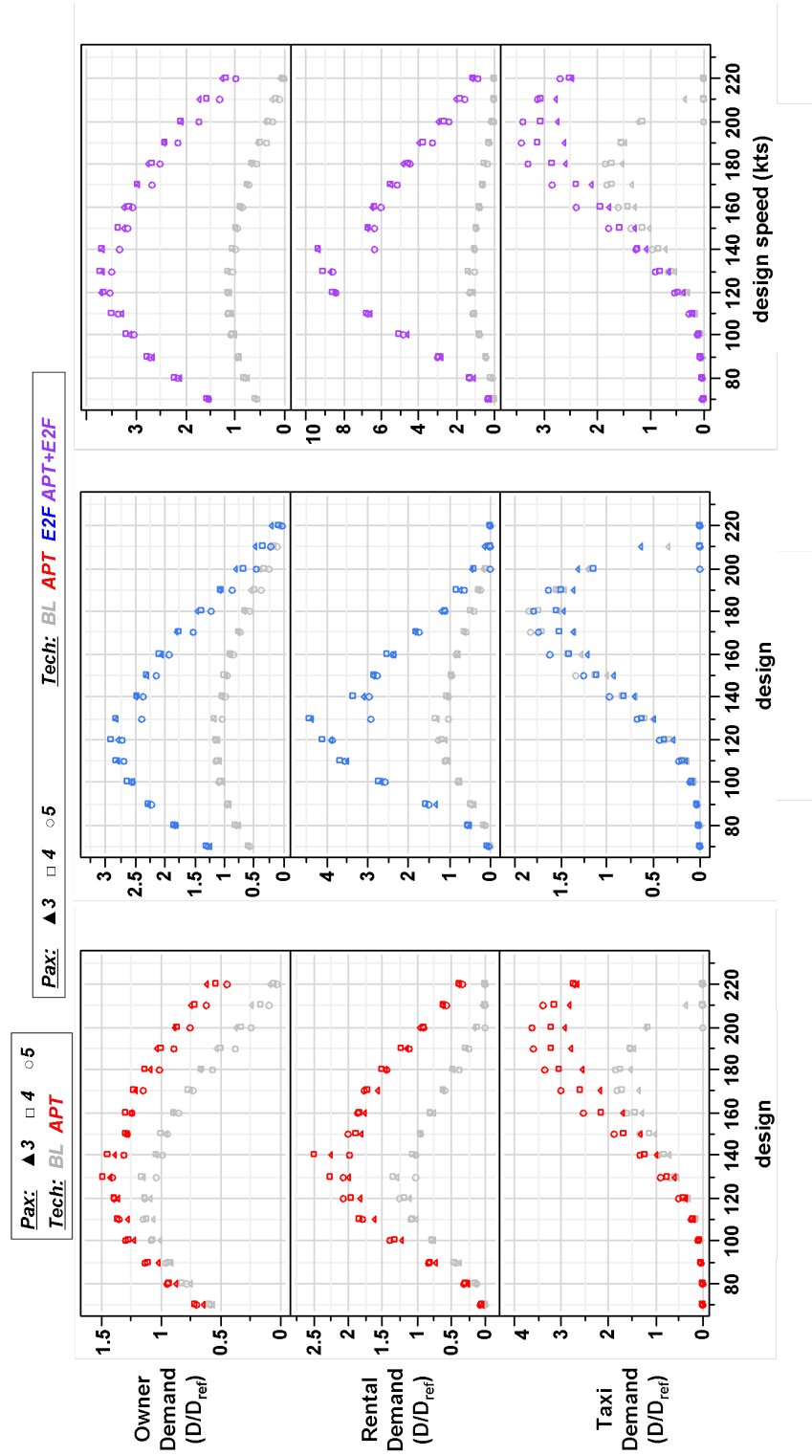
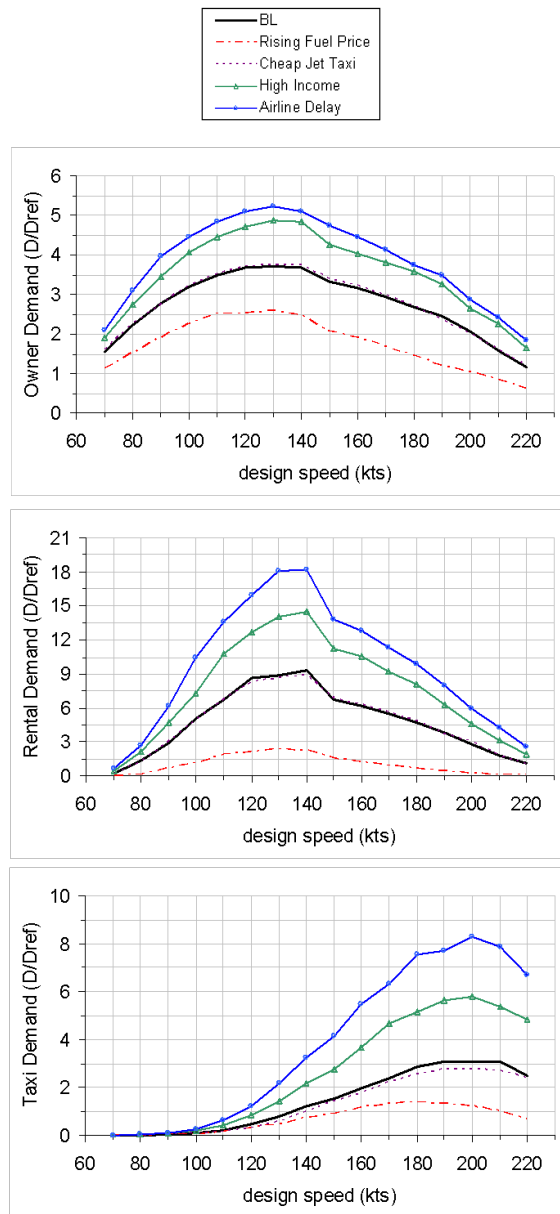


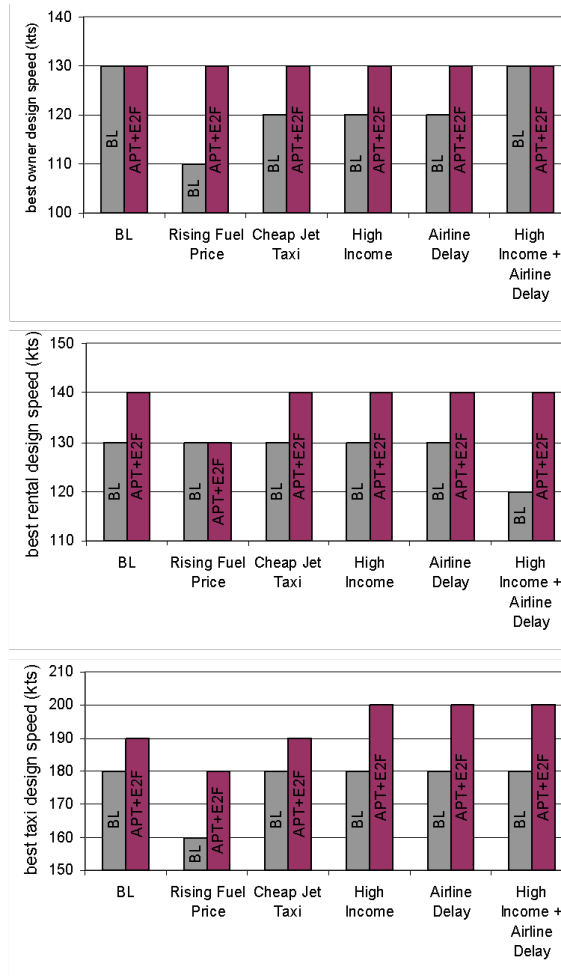
Figure 137: Demand vs. design speed: APT (left), E2F (center), and APT+E2F (right).

C.5 GAP: Driver and Disruptor Scenarios and Multi-System Design



(a) Demand v. design speed, with APT+E2F

Figure 138: GAP driver and disruptor scenario results.



(a)

Figure 139: GAP driver and disruptor scenario results: best design speed.

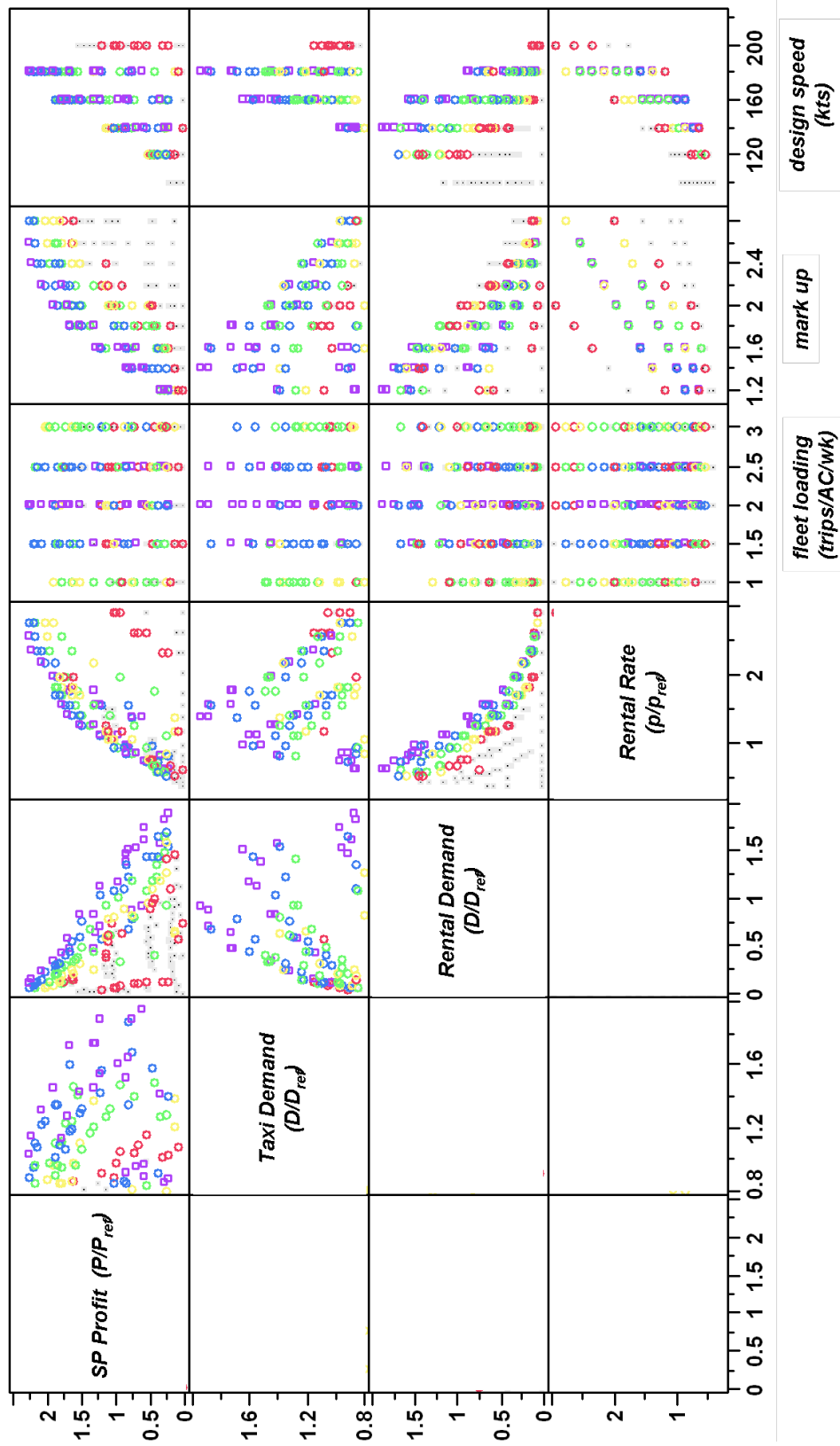


Figure 140: Multi-system design results, colored by s-Pareto frontiers (1-5: purple, blue, green, yellow, red).

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